Aalto-yliopisto
Aalto-universitetet
Aalto University

Master's Programme in Innovative and Sustainable Energy Engineering

Integration impacts of low temperature sub-networks on existing district heating networks

A Swedish Case Study

Tom Antle

Master's Thesis 2021

Copyright ©2021 Tom Antle

Aalto-yliopisto
Aalto-universitetet
Aalto University

Author Tom Antle

Title of thesis Integration impacts of low temperature sub-networks on existing district heating networks

Programme Joint Nordic Master's in Innovative and Sustainable Energy Engineering

Major Energy System Modelling

Thesis supervisors Prof. Risto Lahdelma (Aalto) and Prof. Björn Laumert (KTH)

Thesis advisors Dr. Monica Arnaudo (KTH) and Johan Dalgren MSc (SE)

Collaborative partner Stockholm Exergi

Date 25.06.2021 **Number of pages** 109 / 3 **Language** English

Abstract

As the need to reduce CO2 emissions from the heating sector to meet climate targets grows solutions such as the electrification of heating and low temperature district heating are becoming prevalent. To achieve such emissions reductions within significantly decarbonised district heating networks, it is of increasing importance to evaluate the emissions from electricity production, including the hourly and seasonal variation inherent there. Using a new district in Stockholm, Sweden, as a case study this work examines the interactions between an existing high temperature network and a new, linked, low temperature network serving a temperature efficient district. Particular focus is placed on the effect of heat recovery opportunities created by the new low temperature district on the existing network and peak heat requirements from the existing network, the net CO2 emissions after heat recovery and electricity use, as well as the electrical intensity of heat supplied to low temperature district. After modelling the building heat demands with PlanHeat and simulating the low temperature network in the python environment utilising PandaPipes and the PuLP optimiser, it was found that the emissions reductions depend significantly both utilisation of heat recovery opportunities and the electrical intensity of heating. In addition, it was found that the lowest overall emissions came from the utilisation of waste heat within the existing DHN, while the highest came from the utilisation of an electrically driven sea-source heat pump.

Keywords low temperature district heating, 4^{th} generation district heating, building emissions, 3^{rd} pipe systems, marginal electricity emissions, heat recovery

Table of Contents

Dedication

To my family, our torchbearers

To friends near and far, you are the spice of life

To Renae,
thank you for this journey through Finnish forests and Swedish seas

To those that will,
go forth and build

Symbols and abbreviations

Symbols

α	Heat transfer coefficient (of pipe)
β	Temperature loss across heat exchanger
BB_i	Building Block number *i*
d	Diameter (of pipe)
COP_{HR}	Coefficient of Heat Recovery
E_{FPC}	Electric power in floating point condenser mode (chiller)
E_{HP}	Electrical Power of a heat pump
E_{Pro}	Electrical power of a prosumer
k	internal roughness (of pipe)
L	length (of pipe)
η_{Car}	Carnot efficiency
η_{Lor}	Lorenz efficiency
P_s	Supply Pressure
Q_{del}	Delivered heat
Q_{HP}	Delivered heat from a heat pump
Q_U	Unmet Demand
RC_i	Recirculation (flow, temperature) number *i*
T_a	Air Temperature
T_{ext}	External temperature, of the ground surrounding a pipe
T_g	Ground temperature
T_{high}	Temperature of a condensor
T_{HTR}	Temperature of the high temperature return line
T_{HTS}	Temperature of the high temperature supply line
T_{HWH}	Temperature of highest waste heat
T_{low}	Temperature of evaporator
T_{LTR}	Temperature of the low temperature return line
T_{LTS}	Temperature of the low temperature supply line
T_{LV}	Temperature of Lilla Värtan (bay)
T_{SHR}	Temperature of space heat return line
T_{SHS}	Temperature of space heat supply line

Abbreviations

3GDH	3rd Generation District Heating
4GDH	4th Generation District Heating
AH	After-heater
CHP	Combined Heat and Power
COP	Coefficient of Performance
CV	Control Valve
DCN	District Cooling Network
DCW	Domestic Cold Water
DH	District Heating
DHN	District Heating Network
DHR	District Heating Return (Line)
DHS	District Heating Return (Line)
DHW	Domestic Hot Water
DOT	Design Outdoor Temperature
EU	European Union
FGC	Flue Gas Condenser
FPC	Floating Point Condensation
HDD_{17}	Heating Degree Day, based on 17°C indoor temperature
HOB	Heat Only Boiler
HP	Heat Pump
HT	High Temperature
HTN	High Temperature Network
HTR	High Temperature Return
HTS	High Temperature Supply
LCA	Lifecycle Analysis
LT	Low Temperature
LTD	Low Temperature District
LTDH	Low Temperature District Heating
LTN	Low Temperature Network
LTR	Low Temperature Return
LTS	Low Temperature Supply
MSW	Municipal Solid Waste
NDS	Norra Djurgårdstaden
OSM	Open Street Maps
PH	Pre-heater
QGIS	Quantum Geographical Information System (program)
RCU	Residual Capacity Use
SE	Stockholm Exergi
SH	Space Heating
WHR	Waste Heat Recovery

Figure List

Table List

1 Introduction

1.1 Background

As engineers we engage with technical challenges, and it is easy to become engrossed in the technical details of the problem at hand. This work, and this field, are shaped today by what Scientific American has labeled not merely climate change but an unfolding climate emergency[1] [2]. Even as we work to tackle these issues the global emissions of carbon dioxide continue to rise, reaching 36.4 GT in 2019, excluding land use changes [3]. In 2020 the impacts of the COVID-19 pandemic are expected to reduce global emissions by 2.0-2.5 GT. This level of emissions reduction is similar to what would be required every year to achieve Net Zero by 2050. Unfortunately by December 2020 global emissions were once again higher than in same month the year before [4].

Heating the building sector accounts for a large fraction of global emissions. In 2020 carbon dioxide emissions from energy use in buildings accounted for 2.9 GT/yr or 8.6% of global emissions [5]. In the EU, energy use in buildings accounts for 40% of final energy demand, with residential buildings alone forming 27% [6]. In Sweden, energy services to buildings produce 18% of national carbon dioxide emissions [7]. To reduce the harm stemming from global climate change and reach a point near net zero these emissions will have to be reduced to a very low level.

1.2 Opportunities for Innovation

Sweden is in a unique position to develop new and cleaner methods of heat supply. It has the highest level of district heat network (DHN) penetration in the EU-28 with 48.5% of all heat supplied to residences being supplied by DHNs, with the remaining heat requirements served by the electrical grid and individual heating installations fueled primarily with biomass [8]. In urban areas the DHN supplies a very high fraction of heating, and over 500 cities and towns have a DHN. In Stockholm nearly 90% of buildings are connected to the DHN [9]. Thus DHN are in a position to impact a large fraction of Swedish emissions and represent a substantial investment in social infrastructure [8]. These assets can continue to provide value in a decarbonising world and can form a key link in the drive to higher utilisation of energy resources [5].

Improvements in building construction have dramatically reduced the heating requirements for new buildings since DHNs became established in

[1] This 2021 article "[We are in a climate emergency, and we're going to say so]()" is in reference to a study signed by 11,000 scientists from 153 countries stating that today's changing climatic conditions constitute a global emergency.

the late 1800s and have served as a path to greater efficiency. For example, in Sweden the average existing multifamily residence consumes 135 kWh/m^2/yr of heat, while new mainstream construction techniques allow for buildings with consumption below 30 kWh/m^2/yr [6]. New builds also require a lower heat supply temperatures [10]. These two effects — of greater building efficiency coupled with lower temperature requirements — are putting pressure on traditional 3rd generation district heating (3GDH) as a competitive heating option. Alternative heat supply technologies such as electrically driven air and ground source heat pumps can meet these less rigorous needs more cost effectively [11].

Low temperature district heating (LTDH), one component of 4th generation district heating (4GDH) and an improvement on 3GDH, has been shown to reduce transmission losses and allow for a higher share of waste and ambient heat in a DHN's supply mix [12]. LTDH can also increase the thermal efficiency of a number of heat production methods, from flue gas condensers to solar thermal collectors. As a consequence of the low supply temperatures found in LTDH it is possible that electrically driven heat pumps can become the primary heat supply method. Electrification is noted as a pathway to decarbonisation in heating, particularly in regions with a low carbon electricity supply, as it negates the need for combustion and can provide high thermal efficiencies.

1.3 Problem

The use of electrically-driven heat pumps is widespread in low temperature district heating, either as a centralised production method or as a way of increasing the temperature of supply at the customer. As a part of the heating load is transferred from the existing legacy technologies to the electrical network, this so-called power-to-heat results in an increase in electrical demand in the districts it is applied to. The resulting electrical loads can reach the limits of existing electrical networks in districts not designed for them [13], and the upgrade of national and regional networks to support these loads imposes large socialised costs. The peak heating demand in a Nordic city can be several times higher than its peak electrical demand, so determining the required electrical capacity for LTDH at a time when transport and industry are also electrifying could clarify network build out costs. This issue is particularly pressing in Stockholm, where congestion in the surrounding national grid is expected to limit the addition of consumer electrical capacity through to 2027 [14]. This congestion in the electrical network will impact the use of power-to-heat technologies both by limiting their ability to connect to the grid and by increasing their costs of operation due to an effective supply restriction.

The increasing share of electricity in heat production, both in centralised and decentralised systems, also leads to an increased focus on the emissions created by producing that electricity. In significantly decarbonised DHN, utilising high shares of waste heat and renewable sources as envisioned in 4GDH, the emissions stemming from electricity become increasingly important. An accurate accounting of emissions from both the existing heat production methods and the electricity used in new solutions is required.

1.4 Research Scope

District Heat Networks (DHN) operate at the junction of the heat and electricity systems and as such act in dynamic and complex marketplaces. The European electricity grid, for example, connects many regions with varying technology preferences, producing carbon intensities ranging in 2019 from 8 g/kWh in Sweden to 892 g/kWh in Estonia [15]. Determining the short-term marginal emissions of electricity used for heating is key to determining the net climate impact of electrifying heating. Recent advances in data processing by the organisation Tomorrow have made it possible to determine the average and marginal emissions of electricity demand hourly in a given region to aid in this determination [16]. This is an improvement to analysis desired in several works such as Volkova in analysing LTDH prospects in Tallinn [17] and Brange when investigating the impact of DHN prosumers in Malmö [18].

The net effect on emissions of electrifying heat is not immediately clear without analysis that takes into account the emissions from electricity production as well as heat generation. Many DHNs today utilise a mix of heat generation technologies and fuel combinations, not all of which may have heat or electricity generation as their primary aim. Each individual context produces a different range of carbon emissions [19]. In DHNs that utilise large amounts of waste or ambient heat and where biofuels comprise a large share of combustion fuels, the carbon emissions can be quite low. Since the late 1970s Swedish DHNs have substantially transitioned away from fossil fueled heating, and Swedish DHNs as a whole now have specific emissions approaching those of renewable electricity production [11].

It should be noted that using grid electricity inherently raises the emissions of heating when operating in a decarbonised heating network, even when operating with a Nordic electricity mix. LTDH increases this contradiction as it gives access to even more low carbon heat sources than are possible with conventional 3GDH, however frequently uses electrically driven heat pumps. Details of this contradiction are elucidated further in Section 7: Results.

This is a fine point: new analysis must take into account the challenges, opportunities, and nuances of electrically driven low supply and return temperatures. Low supply temperatures reduce the amount of heat input needed, whereas the lowered return temperatures of LTDH give DHN operators access to new reservoirs of heat in the form of heat recovery options not previously available, both within and without their current production assets. Capturing the operational complexities and values of these opportunities is difficult, and it varies between one operator and the next. Of particular importance to determining an economic impact are the temperature levels that can be used to supply the required heat to a given flow[2]. Clarifying the interactions of a LTD with an existing DHN beyond a net energy requirement has not been seen in other works. This integrated, flexible approach will be useful to DHN operators to understand how the proposed solutions will fit into their existing asset base and operations.

1.5 Research Objective

The aim of this work is to develop a model and metrics to allow a district heat network (DHN) operator to determine the relative cost of heating a new, contiguous low temperature district (LTD). Acknowledging the complexity of the systems DHN operators rely on in their day to day decision making, this work first explores through five scenarios how a single LTD might be heated and second how each heating scenario could impact heat production in the wider and evolving DHN.

Through a case study of Stockholm's proposed Loudden District, this work analyses the impacts of implementing a new low temperature district alongside an existing high temperature DHN. Beyond a net energy requirement, it expresses this analysis on the basis of electrical and net heating capacity requirements, carbon dioxide emissions, and the supply and return temperatures of the LTD. These impacts are evaluated with integration into an existing DHN in mind. Recognising that there are heat recovery opportunities available in many existing operations, and that Low Temperature District Heating (LTDH) opens further sources to utilisation, it also determines the amount of heat recovery at different temperature levels enabled by the LTD's integration with the existing DHN.

1.6 Methodology

In its application to the energy requirements of the new Stockholm district of Loudden, this work developed the space heating (SH) and domestic hot water (DHW) demands for a new high efficiency district using PlanHeat [20], a QGIS plug-in developed in Python.

Five heat supply scenarios were developed to model the supply of LTDH to the district. To determine the mass flow, pressure, and temperature conditions throughout the LTDH, a DHN pipe network was developed in the Python environment making use of the pandapipes library [21], built upon

[2] For example, a LTDH supply may only have to be heated to 65°C, while a conventional DHN supply may have to be heated to 100°C. Providing the higher temperature may cost the operator more.

the better known pandapower library [22], and a heat flow analysis was conducted. In each of the five scenarios, the Python PuLP optimiser [23]. was used to determine mass flow rates of high temperature supply, high temperature return, a mid-temperature waste heat stream and heat pump electrical power. Data streams from the year 2020 were used to impart realistic variation in the model inputs. A sensitivity analysis of key parameters was performed for the relevant scenarios.

The results of each scenario are presented in a manner such that a DHN operator could determine the cost/benefit impact of each scenario to their operations. The scenarios are not ranked against one another, but their performance is presented for discussion in Section 6: Results.

1.7 Thesis Structure

The introduction outlined the broad decarbonisation challenge facing the heating sector as it transitions to a low emissions world. The specific background to this transition with respect to current technologies in existing DHNs and future heating arrangements is discussed in Section 3: Theoretical Background. In Section 4: Case Study, the case study district of Loudden is introduced. In Section 5: Scenario Descriptions, five relevant arrangements are developed as scenarios: high temperature network (HTN) supply, utilising HTN return flow, utilising a waste heat source, electrifying heating with a sea-source heat pump, and implementing several prosumers. Section 6: Modelling features a description of the modelling tools, their use, and the scenario implementation details while Section 7: Results articulates the results of the scenarios with specific reference to emissions, heat and electrical capacity requirements, electrical intensity of heating, and the heat recovery opportunities in relevant temperature bands and discusses descriptions of the chosen metrics. Section 8: Sensitivities illustrates the impacts of several design points and draws attention to the impacts of building design and network control and Section 9 draws final conclusions. Extensions of this work are proposed in Section 10: Future Work.

1.8 Limitations

The boundaries of thesis work do not extend beyond the modeled LTD and the discussion of impacts that lower temperature flows would have on the DHN operator. For example, it does not account for the offset emissions that a change of electricity production in a CHP plant would produce in the European grid. The heat supply scenarios considered here all include a distribution network with no temperature boosting at the customer and no customer cooling demand was included in these scenarios. A single supply temperature was supplied to each customer.

The capital and operational costs of the scenarios proposed are not considered.

2 Theoretical Background

2.1 District Heating Networks

District heating networks (DHN) are comprised in essence of heat production units and underground pipes that deliver hot water to customers and return cooled water back to the heat production plants. While the first networks were constructed in the late 1800s as steam delivery systems, many modern Scandinavian networks such as Stockholm and Helsinki were initiated in the 1950s. These networks utilised pressurised water above 100°C to transfer heat and were typically fueled by coal heat only boilers (HOBs) or combined heat and power (CHP) plants that produced both heat and electricity [12]. Evolutions in building and network design including insulated pipes have enabled lower supply temperatures over time with many systems today operating with 75-90°C supply temperatures. Today DHNs supply a large fraction of Swedish heat demand, and Sweden delivers the 5th most district heat by counties globally. The evolution of DHN from 1st generation (steam supply) to 2nd generation (pressurised hot water) and 3rd generation (lower temperatures) district heating (3GDH) has progressed to the point that most systems today are complex infrastructure systems [24]. With the development of more complex networks additional heat sources beyond fossil fueled boilers were incorporated, with the large scale use of industrial waste heat in Gothenburg and Malmö being notable examples.

A key consideration in the discussion of district heat networks is that they are fuel-agnostic [8], meaning that they transport heat energy regardless how it is created, or with how many emissions. In this respect they are aligned with the electrical network. This is different than, for example, an individual boiler in a residence that is designed to run on a single fuel.

District heating to buildings supplies two main building services: space heating (SH) and domestic hot water (DHW) production. The designs of these two services determine the supply requirements to a building from the DHN, and design standards for buildings and networks have developed together.

DHNs suffer from distribution losses due to the temperature difference between the hot fluid within the pipes and the lower temperature of the soil. In Sweden losses account for 12.3% of all DHN production [19]. The ground temperature changes throughout the year in response to the air temperature, solar insolation, and heat loss to the atmosphere. At depths less than 16m, well within the depths of DHN pipes, the temperature of the ground fluctuates in response to the air temperature, with decreasing seasonal change as the depth increases [25]. Decreasing the supply and return temperatures in the network reduces distribution losses. Longer, larger, and more looping networks tend to have more losses and conservative design decisions, or anticipating future growth, can lead to oversized pipes that have a higher relative heat loss.

Several fluid circuits exist in most DH network and building systems. In the discussions below the term “primary” will refer to flow in the DHN, “secondary” will refer to flow in the SH circuit of individual buildings, and “DHW” to flow in the DHW circuit of individual buildings.

2.2 Building Heat Demands

Previously divided into three climate zones, in 2015 Sweden added a fourth climate zone in the south. Seen in Figure 1, the climate zones define the energy consumption requirements that new buildings must adhere to. In Zone 3, where the majority of Swedish residences are located [26] the requirements are as seen in Table 1 below.

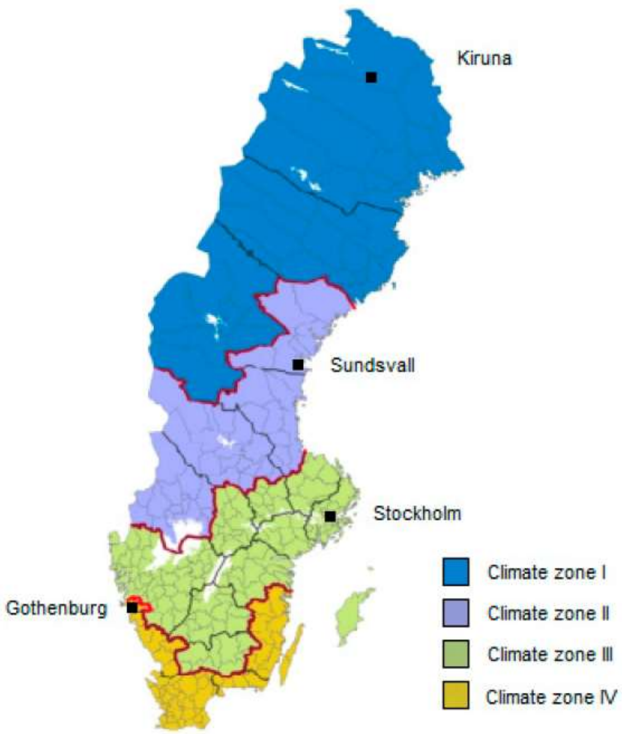

Figure 1: Building Code Climate Zones in Sweden since 2015 [27]

Table 1: Thermal Energy Consumption Limits in Climate Zone 3 by Building Use [26]

Thermal Energy Use ($kWh/m^2/yr$)	Single Family	Multi-Family	Non-Residential
Electrically Heated	55	50	50
Non-Electrically Heated	90	80	70

Of note is that “Electrically Heated” includes buildings heated by both direct electric heating and by heat pumps, two technologies with vastly different heat supply efficiencies. Buildings supplied by DHNs, whatever the production mix of the network, are classified as Non-Electrically heated. Niskanen, in a review of Swedish energy efficient building regulation, notes that for many decades building energy use regulation was aimed at maximising a long term cost/benefit analysis between construction cost and energy cost in the interest of personal and national economics [7].

While Table 1 indicates that multifamily buildings should be constructed with lower heat demands than single family homes, this is not borne out in constructed dwellings. As seen in Figure 2 multifamily buildings of all ages consume more thermal energy of single family homes of a similar age. A noteworthy trend is the decrease in heat demand, particularly in multifamily buildings, over the previous 8 decades. As a large fraction of the Swedish housing stock was constructed in the period 1960-1975 average building performance has not dropped as much as the trend would suggest. The average Swedish multifamily home in 2017 consumed 135 $kWh/m^2/y$ of heat for SH and DHW while the average single family home consumed 106 $kWh/m^2/y$ [6].

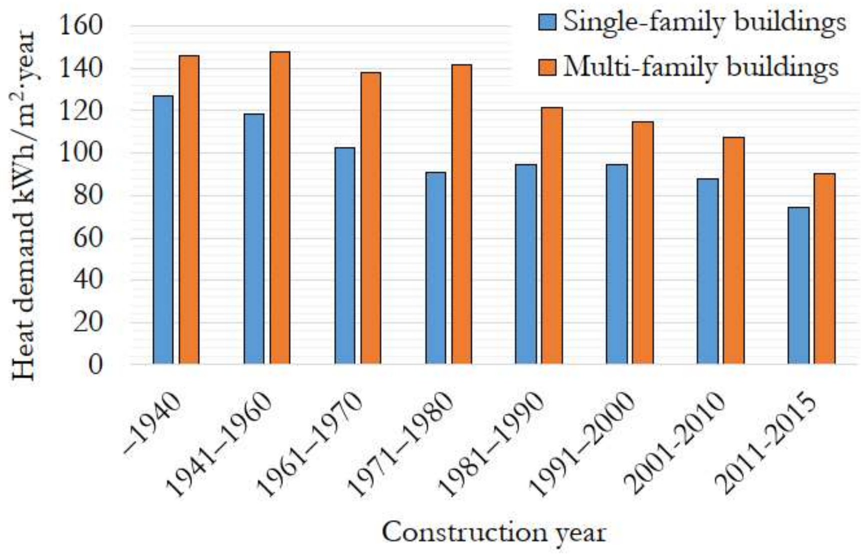

Figure 2: Thermal Energy Use of Swedish Buildings by Build Year [6]

2.2.1 Space Heating

SH maintains the indoor temperature of the building at a level comfortable to its occupants, typically around 21°C [28]. To achieve this, hot water is circulated through radiators in the building where the temperature difference between the radiator and the interior air causes heat transfer to the air.

A building's SH system must be designed to maintain indoor comfort at the design outdoor temperature (DOT), which is given at a specific location and is based on historical climatic conditions. The DOT is not the lowest temperature encountered in a location, but is the 99.6th percentile coldest temperature seen in the historical record. In Stockholm the DOT is -20.1°C [29].

The secondary circuit temperature profile, that of the interior SH circuit, is characterised in the form "80/60". This denotes that at the DOT the SH circuit will be supplied with 80°C water, and will return 60°C water from the radiators. It is worth noting that the DOT is rarely encountered, so the temperatures in the secondary circuit are nearly always lower than is indicated by this label.

As can be seen below in Figure 3 the secondary supply temperature is at a maximum at the DOT of -20°C and decreases linearly to a minimum at 17°C. While it is common to design the radiator heating system for an indoor temperature of 21°C, the designer expects a certain amount of free heat to be generated in in the building. This can come from sources such as the human occupants themselves, heat given off by appliances, and heat losses from the

DHW system. A good estimation for this amount of heat is 4°C, and therefore the SH system is designed to provide no heat above 17°C [30].

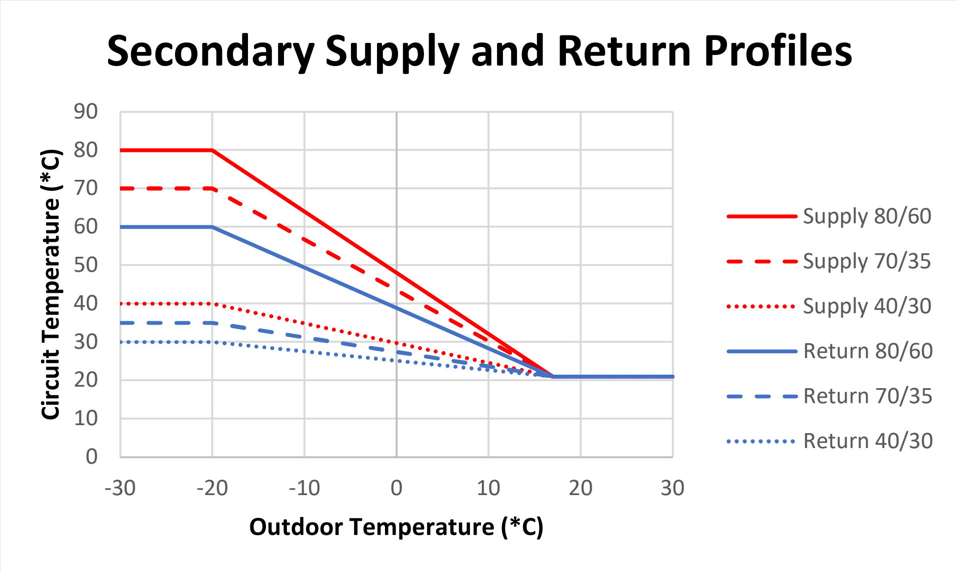

Figure 3: Secondary Supply and Return Temperatures for different profiles. Adapted from [10]

It is important to note that the primary return temperature from the SH exchanger is dependent only on the return temperature of the secondary circuit, not on the secondary supply temperature (nor on the primary supply temperature). This can be seen below in Figure 4 for a 60/40 secondary circuit. The design standards for Swedish DH substations specify that the primary return temperature can be no more than 3°C higher than the secondary return temperature [28]. It is worth noting however that in the effort to reduce the primary return temperatures from customers reducing this difference to less than 3°C by increasing the number of thermal lengths in the SH heat exchanger would provide a significant benefit [24].

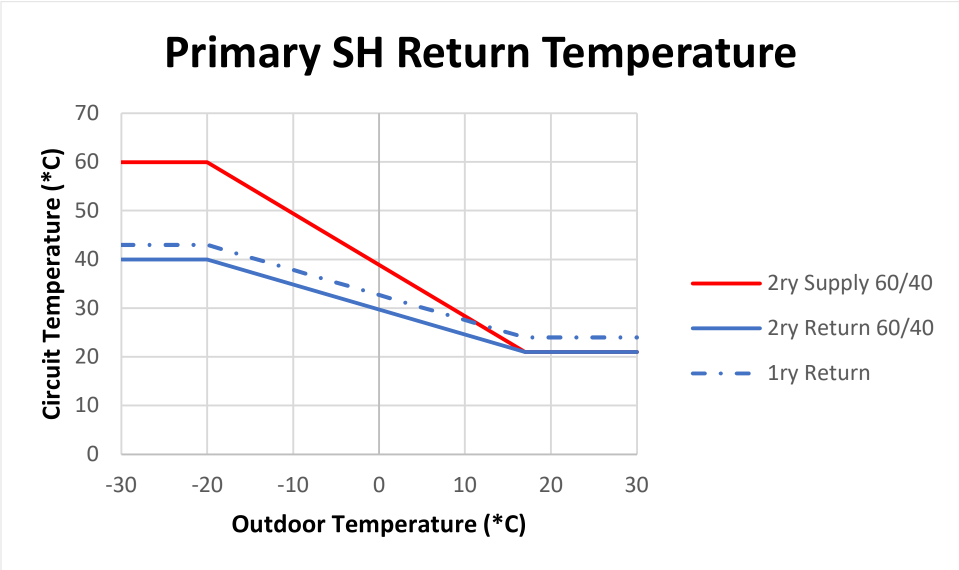

Figure 4: Primary Return Temperatures for a 60/40 SH arrangement

Since DHNs have been implemented in the late 1800s, three trends have developed to change the design of SH radiators. First, buildings have become more insulated and therefore require less heating. The SH radiators are sized for the maximum heating demand [24], so newer buildings required less heating power. For the same legacy radiator sizes this meant lower secondary supply temperatures could be tolerated. An increase in the demand for thermal comfort within buildings has improved radiator placement and operation. This in turn has lead to radiators better placed to more effectively work with building ventilation system to maintain thermal comfort rather than relying on a poorly placed, very hot, radiators. Increasing the number of thermal lengths (the relative size) allows for the desired lower return temperatures in the radiator, which results in further lowered secondary return temperatures. Floor (or wall) heating use those surfaces as very large radiators that can be maintained at near to ambient temperature, in some case requiring no more than 37°C secondary supply temperature to maintain indoor temperatures of 21°C, a far cry from the 80°C temperatures sometimes required in older installations.

As SH is dependent on the outside temperature, during the summer period no SH is required. It is common for building operators to physically isolate the SH system with valves from the DHN during this time to avoid being charged for leakage flows or to avoid overheating of the building due to malfunctioning substations. While the timeline for isolation is decided by the individual building operators, the DHN operator will start to reduce the supply temperatures as outdoor temperatures rise in the late spring and increase the supply temperature as the outdoor temperature falls in the autumn. It can be said that the heating season ends when the daily temperatures rise above 10°C and begins again when the temperatures drop below 12°C [30]. In Stockholm this typically results in a heating season from the beginning of September to the middle of May.

2.2.2 Domestic Hot Water

DHW for potable and non-potable uses is heated together in buildings, necessitating that the entire DHW system be treated as a potable system. There are two health concerns that the DHW system must avoid. The first is the risk of scalding due to DHW that is too hot, leading to the requirement that DHW should not be provided hotter than 65°C [31]. This is generally not a problem, other than in some older three stage substations [10]. The second major concern is the potential growth of legionella bacteria, which can cause a type of pneumonia called Legionnaire's disease in humans. Design requirements to limit the growth of Legionella in potable water systems impact the design of DH substations significantly. As the bacteria begin to die at temperatures above 46°C [32], it is a requirement in Swedish systems that the temperature of the DHW system at all points should be maintained above 50°C [3] [33]. This leads to a practical lower temperature limit for DHW supply of 55°C [34] to account for heat losses in the DHW distribution system. As this temperature level is hotter than the required SH supply temperature at many temperatures (as seen in Figure 3), the DHW often becomes the limiting supply temperature to a substation. It should be noted that Danish regulations allow for a DHW temperature of 45°C [35], a difference that could lower the DHN supply temperature by 5°C.

A DHW pipe without flow through it, such as a pipe to a closed tapping point, will lose heat to the building envelope until the water temperature drops to the ambient temperature surrounding the pipe. A common method of maintaining the minimum 50°C temperature is to include a recirculation loop to the DHW heater so that hot water can be flushed through the system continuously. This method also has the advantage in large buildings that hot water is available to all tapping points quickly, as the Swedish building code requires that hot water be available within 10 seconds [36]. Including a recirculation line maintains the temperature of the DHW system but does not mitigate heat loss from the DHW pipes, indeed heat losses increase. Heat loss from the DHW pipes is undesirable for several reasons.

- Heat losses represent an uncontrolled flow of energy and so are undesirable when attempting to reduce and monitor building energy consumption.

[3] The bacteria begin to increase in numbers at temperatures below 46°C and decrease at temperatures higher than 46°C. Higher temperatures cause the bacteria to die faster. For practical purposes temperatures of 60°C and above are sufficient to cause a very rapid decrease in the numbers of bacteria in a given sample [28].

- While some of the heat losses from the DHW could reduce the SH demand by heating the building envelope, not all of the DHW system is within the heated building area and so some of the energy will be lost to the ambient.
- Heat losses in the DHW system require reheating in the substation. Reheating DHW from 50°C to 55°C produces a high primary return temperature near 50°C from the DHW heat exchanger, as will be discussed further in Section 2.2.3: Customer Substations.

Heat losses from the DHW system can be significant. Although the Swedish building code provides a design estimate of 4 kWh/m²/yr studies have found values ranging from 0.5 kWh/m²/yr to 76 kWh/m²/yr [36], [37]. This latter figure is enough heat to provide SH and DHW in many modern buildings. Average values of buildings before 2011 indicate DHW losses of 14 kWh/m²/yr, while buildings constructed after 2011 showed DHW losses of 6 kWh/m²/yr. Both time periods showed a wide range, and several of the poor performing buildings were built recently. Controlling the heat loss from the DHW system is particularly important in LTDH systems as the high return temperatures that reheating DHW causes results in an increase in the primary return temperature.

The DHW heat demand is seasonally affected by the incoming potable water supply temperature, particularly if the water source is surface water rather than ground water. With a fixed delivery temperature of 55°C the power required to heat the DHW varies with the incoming water temperature. A year round reference temperature of 10°C is used in Swedish standards [28].

2.2.3 Customer Substations

The design goal of a substation is to ensure that the demanded heat energy is transferred into the customer’s heating system at the temperature levels required to provide DHW and SH. A goal that has always been good practice but is gaining importance is to use as little mass flow as possible to provide the demanded heat, in order to reduce the size of components in the DHN and so their cost. The primary method of reducing mass flow is to cool the primary flow as much as possible. This also reduces the return temperatures [38]. There are a large number of substation designs in use and proposed, but only three will be described in detail here: The Parallel, the 2-Stage, and the Russian 3-Stage. These three designs have been selected first because they allow for an explanation of the operation of DH substations to proceed step-by-step, and second because they offer a viewpoint into three evolutions of temperature efficiency. The parallel substation is the most widely used design in Sweden today and is featured in many national substation design guidelines [28]. The 2-Stage is the next most common and can be found in larger buildings [39]. Lastly the Russian 3-Stage is not shown in Swedish manuals, although it has been investigated by Johansson of Lund University, and is the most temperature efficient substation design compared to a wide selection of options [38].

There are two divisions within DHN substation connections: indirect and direct. Indirect connections are by far the most common and use a heat exchanger to separate the primary flow in the DHN from the secondary flow within the customers pipes, that is the fluid in the DHN never enters the customer's pipes. With direct connections there is no exchanger between the DHN and the customer. The fluid from the DHN therefore enters the customer's piping before returning to the DHN. Direct connections for SH have been proposed as a method to reduce the temperature loss through the substation as the temperature drop across the heat exchangers is avoided but entail the DHN operator in giving up some control over the network's operation to their customers [40]. An indirect connection preserves the physical barrier of the heat exchangers and substation equipment that allows the wider DHN to be isolated from failures within the customer's secondary network. It is noted that a substation utilising a direct connection for SH will still require a heat exchanger for the DHW service to separate the potable and non-potable services. Only indirect connections will be discussed here.

2.2.4 Parallel Substation

The most common substation in Sweden, and the simplest arrangement, is the parallel substation [39] as seen below in Figure 5. In this arrangement there is one heat exchanger for the SH and one for the DHW demand, both supplied with the primary (pink) supply temperature. On the right, the secondary circuit supplying SH (green) is heated and circulated to the building radiators. The temperature in the secondary circuit depends on the outdoor temperature as discussed in Section 2.2.1: Space Heating, and the control valve (CV) is opened and closed to meet the SH supply temperature at T_{SHS}. The primary return temperature from a well-designed and well-functioning SH exchanger should be no more than 3°C above the SH return temperature T_{SHR} [28].

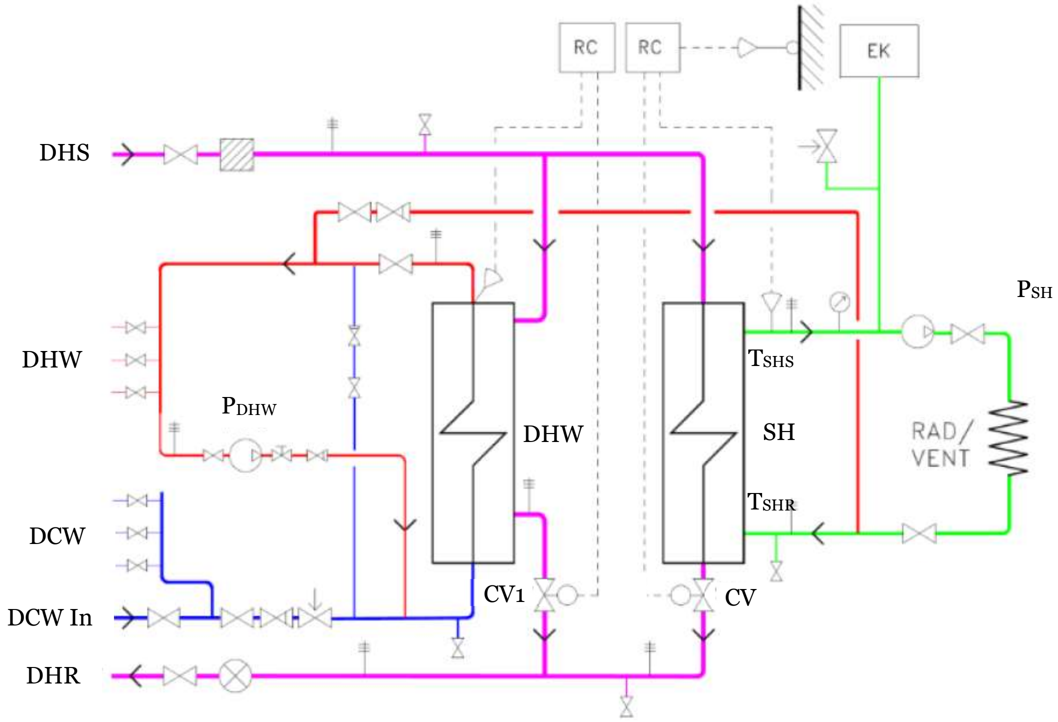

Figure 5: Parallel Substation Connection [39]

On the left of Figure 5 the DHW (red) can be extracted by the user at the DHW tapping points. A constant temperature above 50°C is maintained by recirculating the DHW with the pump P_{DHW}. When no DHW is tapped, the primary return temperature from the DHW exchanger will be very close to 50°C and the primary flow through the DHW heat exchanger will be only enough to make up for heat losses in circulation. When DHW is tapped make-up DCW (blue) is added to the system and is mixed with the recirculated DHW before being heated. The substation should be designed such that the primary DHW return temperature is no more than 12°C above the combined temperature of the recirculated DHW and the incoming DCW [10].

The primary return temperature at DHR is the mass weighted combination of the primary SH and DHW return temperatures. The SH return temperature can dominate this mixture, for example when the SH demands are much higher than the DHW demands. This can occur in older less insulated residential buildings during the heating season. However, at times with relatively higher DHW production than SH demand, such as newer office buildings, the DHW return temperature will play a more relevant role. Outside of the heating period, when no SH is required, the primary return temperature is equal to the DHW return temperature. Generally, in LTDs more efficient building design corresponds to reducing the fraction of SH in the total building demand [38]. For example, SH makes up as little as 45% of annual energy consumption in a newly built LTD in Tallinn, Estonia [41].

This is in contrast to older districts where SH could be expected to form 90% of the annual energy demand [6].

There are two shortcomings in the parallel substation. The first is that the incoming DCW is mixed with the recirculated DHW prior to being warmed by the primary flow in the DHW exchanger. This raises the minimum temperature in the system without reducing the heating load and so creates a less temperature efficient system [10].

The second shortcoming is that neither the SH nor DHW path allows for reuse of the return temperature for another service. As can be seen in Figure 6, below there is ample opportunity for this, as return flows could be used to heat services with temperature requirements below them (less the temperature loss in the heat exchangers). Two cases are identified:

- The DHW recirc return (when no DHW is tapped) is available at 50°C and could be used to heat SH at outdoor temperatures above -8°C.
- The SH return at all temperatures during the heating season (<17°C outdoor temperature in Figure 6) is hotter than the minimum DHW return temperature and could be used to heat the incoming DCW to a certain degree.

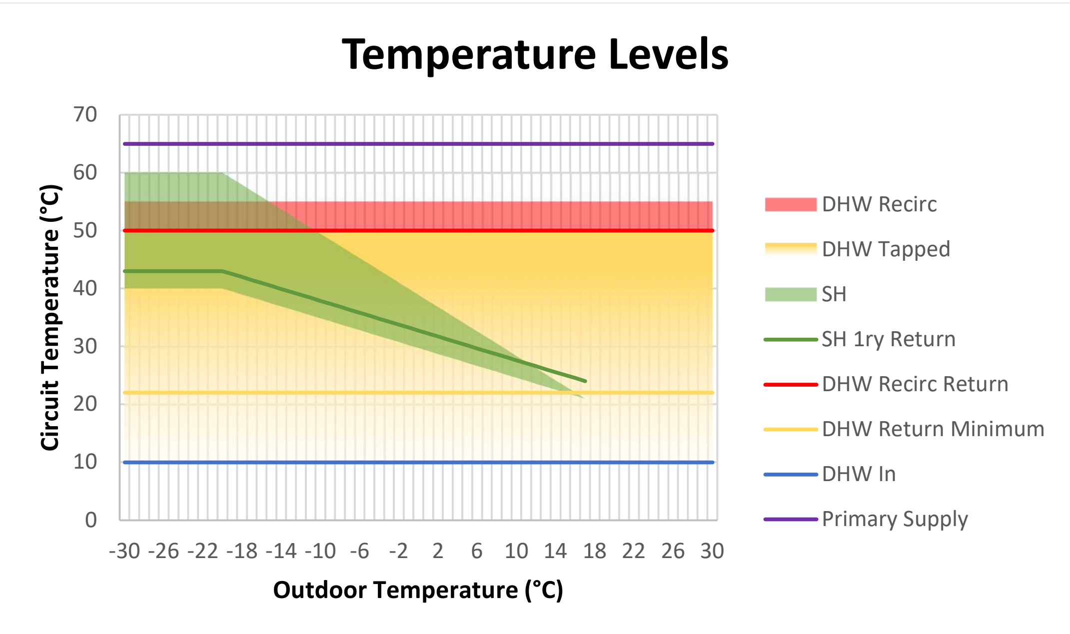

Figure 6: Temperature Overlaps in a Parallel Substation with a 60/40 SH scheme

It is noted in Figure 6 that the DHW return temperature could vary between the minimum and the recirc return temperature in proportion of the volume of tapped DHW and the recirculated flow.

Reducing the SH return temperatures, as is the goal with many 4GDH efforts, reduces the benefit that using SH return flow to preheat DHW flow provides [39] as there is a smaller temperature difference between the SH primary return temperature and the minimum DHW primary return temperature. This effect can be seen in Figure 7, which shows a low temperature floor heating scheme of 37/21 providing a primary SH return temperature of 24°C throughout the year. This is much closer to the minimum DHW return temperature of 22°C than in the 60/40 scheme, which provides a SH primary return temperature of 44-24°C depending on the external temperature. Importantly it is only the SH primary return temperature that gives this effect, rather than the supply temperature.

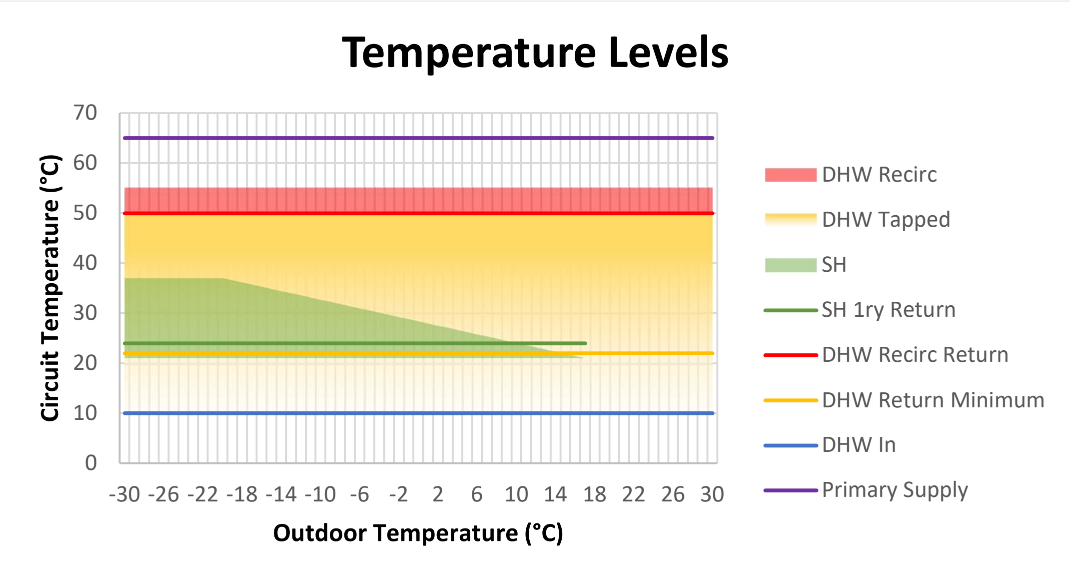

Figure 7: Temperature Levels in a Parallel Substation with a 37/21 floor heating SH scheme

2.2.5 2-Stage Substation

An improvement on the parallel substation, in that it addresses several shortcomings listed above, is the 2-stage substation seen below in Figure 8. On the left of the figure the DHW heat exchanger seen in the parallel substation is divided into two exchangers in the 2-stage substation: a preheater (PH) and an afterheater (AH). This allows the incoming DCW (blue) to be heated prior to mixing with the recirculated DHW (red), and this heat can be provided in part by the primary SH return. In the case of no DHW tapping the 2-stage substation functions as a parallel substation, however when DHW is tapped the primary return temperature is lowered by using the combined return flows to heat the incoming cold DHW.

This arrangement does not, however, allow DHW primary return to be used to heat the SH circuit, and so a heating benefit is not provided when the temperature of this flow is mixed with the SH primary return while the temperature is lowered. While the amount of DHW recirc energy available would be a small fraction of SH demand in older buildings, as discussed in newer buildings it is a more significant opportunity. Utilising the primary return from the DHW recirc also lowers the primary return temperature, a significant objective in LTDH.

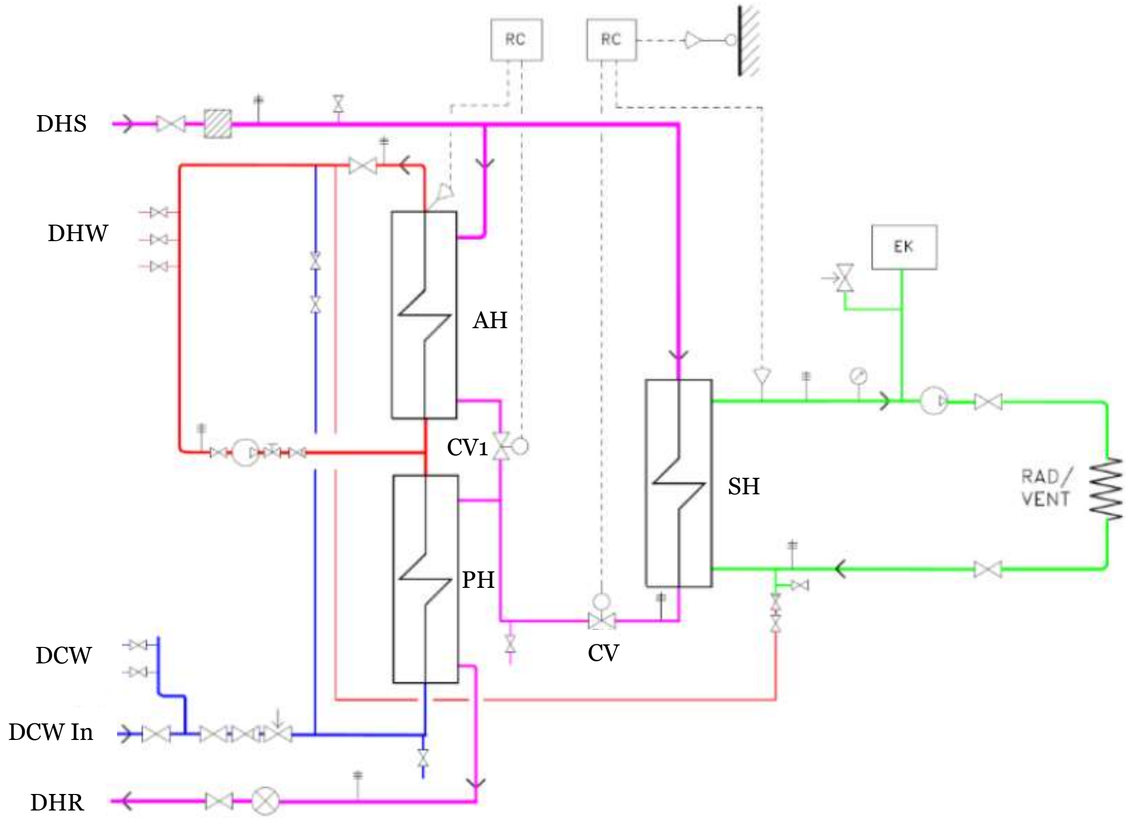

Figure 8: 2-stage Substation Connection [39]

2.2.6 Russian 3-Stage Substation

A substation design that addresses all of the shortcomings noted above is the Russian 3-Stage connection, shown below in Figure 9. This substation design permits the temperature levels produced in normal operation of a building to cascade through the three exchangers AH, SH, and PH while allowing the energy delivered to each service (DWH and SH) to be controlled separately.

For example, the DHW AH primary return can flow to the SH exchanger thereby utilising its still-useful temperature of 50°C, while additional primary supply can flow to the SH through R1 as needed. This marks an improvement from the traditional Swedish 3-Stage substation (as described in the Svensk Fjärrvärme – Substations standard [39]) that lack this AH bypass. Without this bypass additional controls and piping are required to prevent overheating of the DHW supply when SH demand is high and DHW demand is low as all flow to the SH must go through the AH.

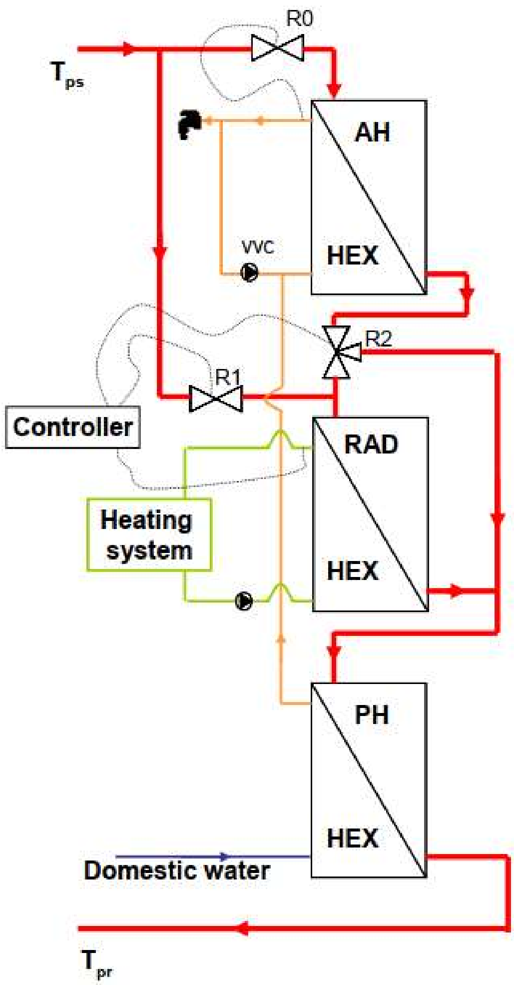

Figure 9: Russian 3-Stage Connection [10]

2.3 4th Generation District Heating Networks

The concept of 4th Generation District Heating Networks (4GDH) was described by Lund, Werner, and others in an influential paper from 2014. The key parameters in 4GDH included not only higher reliance on renewable heat sources and lower temperatures, but also more energy and temperature efficient building stock. Parameters such as an average annual return temperatures of 20°C and building heat demand of less than 25 kWh/m²/y are foreseen [12].

While reducing energy consumption and the need for high temperatures is a key pillar in the transition to renewable heat sources, it can have impacts on the existing DHN delivery model. When 4GDH building stock is added, particularly in a large segment such as a new development, to an existing DHN the linear heat density (typically measured in MWh/m on an annual basis) of that part of the network decreases relative to conventional buildings. This is due to a lower energy demand due of the 4GDH building stock combined with a network of the same length as would be utilised otherwise. This has two effects. First, the fixed costs of that section of the network are spread out over fewer MWh of heat distributed. This results in a higher fixed cost charge. Second is that the relative thermal losses in that part of the network will increase[4].

Unfortunately for the DHN operator, much of the equipment and design that determines the temperature efficiency of a customer's building, such as the design and correct operation of the substation, is not within their purview. The ownership and therefor operation, maintenance, and tuning of building substations is typically by the customer. Historically many DHN tariffs have charged only for the energy use and peak connection power, but not the amount of flow that a customer uses or the return temperature[5] [42]. However in 2016 Song found that half of DHN operators in Sweden used a flow component in the tariff structure [43].

Two of the key design decisions are the type of substation and the thermal length of the exchangers in them and the building. The more complex substation design such as the 2-stage and 3-stage include more components and controls, thereby increasing cost. Increasing the thermal length of exchanger by 1.5-2x in the substation and 1-2x in radiators, described by Averfalk as essential improvements for 4GDH, also increase cost to the builder [24].

These split incentives may contribute to the astounding 74% of substations that contain some erroneous functions [24], such as incorrect placement of valves and sensors, co-current rather than counter-current heat exchanger installation, failed valves and sensors, or bypass flow between the primary supply and return [42]. Although DHN operators may have some influence in the design of the substation, the final investment decision and operating responsibility is the owners' and more capital intensive improvements can be a challenge to implement.

Stockholm's DHN today exhibits many of the characteristics of 4GDH as defined by Lund including utilisation of waste heat, incorporation of a DCN, biomass CHP and HOB plants, and prosumers within the network. However, the supply temperatures of Stockholm's DHN have not yet reduced to those identified in 4GDH scenarios due to the older building stock that it must serve [12].

---

[4] The absolute losses from that section of pipe will remain the same if the fluid temperatures do not change, as the heat loss between fluid and ground depends on the temperature difference.

[5] The flow used and the return temperature are inherently related for a given supply temperature and energy demand. If a large temperature drop on the primary side is achieved in the substation then this will result in both a low return temperature and a smaller volume of water utilised to deliver the demanded heat.

2.3.1 Low Temperature District Heating

Low temperature district heating (LTDH) is a component of 4GDH. The main characteristic of this method of heat distribution is a lower supply temperatures than in previous iterations of district heating network design [12], enabled by more efficient building design. With suitable building design this also results in lower return temperatures in the network. Some authors have noted that while low supply temperatures are thought of as the hallmark of LTDHNs, low return temperatures are equally as important to the sustainability of the system.

The low temperatures in the LTDH result in two main effects from a thermal energy standpoint:

- A wider variety of sources able to supply heat to the network
- A reduction in thermal losses during the distribution of heat

Heat sources can be utilised directly by the LTN if the source temperature is higher than the LT supply temperature. This might include:

- Flue Gas Condensing (FGC) in CHP plants[6]
- Industrial or commercial waste heat
- Solar thermal systems
- Other HOB plants
- Back pressure turbines in CHP plants

Generally, a lower return temperature from the LTN makes these processes more thermally efficient as well, becoming the inlet temperature to the process and the coldest sink temperature. In the case of a back pressure turbine a lower return temperature can increase the Power-to-Heat ratio of the plant [44].

However, even if the heat source has a lower temperature than the LT supply temperature, the lower supply temperatures of LTDH increase the efficiency that a heat pump can boost the temperature with. These sources might include:

- Ambient reservoirs of heat such as the ground, water, and air
- Low temperature waste heat sources
    - From chillers that normally reject heat to ambient conditions using a heat pump
    - From industry that release waste heat to ambient conditions
- Low temperature accumulated sources

[6] This is particularly valuable in Sweden as the MSW and biomass that provide much of Sweden's district heating are high in moisture, and so can produce a higher fraction of FGC heat than drier fuels [5].

- From WWTP and effluents
- From subway systems

Lower supply temperatures improve the coefficient of performance (COP) of heat pumps and efficiency of solar thermal collectors [17], in many cases allowing for economic feasibility. Lower supply temperatures also make heat recovery from low temperature reservoirs of waste and ambient heat possible directly. In previous transitions to lower supply temperatures DHNs advantage was made of stepped temperature levels with a cascade connection to better utilise heat in the network [40]. As 4GDH temperatures approach those of the building envelope, low temperature districts (LTDs) have the capability of acting as a cooler for higher temperature networks while still producing revenue from the sale of heat.

LTDH can also impact the electrical energy use by pumps of distributing heat throughout DHN. While it is true that generally LTDH results in a lower temperature difference between the supply and return temperatures than in previous DHN designs [45], this depends on the operating temperatures in the specific network throughout the year. The power consumed during distribution depends on the pressure losses in the network, which in turn depends on the design and in particular the pipe diameters as well as the mass flow required to provide the demanded heat with the given temperature drop. A lower temperature drop, like those commonly seen in LTDHN, will require a higher mass flow rate. All else being equal this will increase the amount of pumping power required. With new installations this issue can be mitigated somewhat by designing larger pipe diameters, although this presents its own challenges for maintaining the required temperatures throughout the network as well as increasing the network heat losses.

The higher pressure losses in LTDH systems can also be mitigated by the use of plastic pipes, as opposed to conventional steel pipes. Plastic pipes are less rough on the inside pipe surface than steel, for example with roughness of 0.0015 mm as opposed to 0.04 mm, and so result in less pressure drop along the pipe. The use of plastic pipes are enabled by the low temperatures of LTDH, with plastic pipes able to operate with temperatures below 80°C long term. Plastic pipes can have a reduced pressure range than steel pipes, which can become an issue in LTDH as noted above, but this can be mitigated with lower system pressures and more booster pumps. Plastic pipes also offer some additional insulation benefits as the plastic material is less thermally conductive than steel, with PVC having a coefficient of thermal conductivity of 0.19 W/mK and steel 45 W/mK. Plastic piping can also have a lower installation cost than comparable steel piping [46].

Extensive work investigating how to produce lower return temperatures from DHN has been carried out, for example in building substation configurations [10] and by using energy cascades in new [41] and existing [40] buildings.

Previous work has also demonstrated that existing electrical networks can become overloaded on a district level if heat pumps, in this case waste heat recovery, are added to existing buildings as a heating solution to offset use of 3GDH [47].

Due to higher mass flow rates seen in LTDH, a drop in return temperature from a LTD will affect the combined return temperature more than from a HT district. As LTD are added to a cities DHN, their effects will be felt sooner than their heat demand fraction would indicate.

DHN's with supply temperatures below 55°C, that is below the DHW supply temperature, have been characterised by Lund as ultra-low temperature district heating [48]. These systems require a temperature booster at the customer, for example a direct electric or heat pump water heater. The main advantages of these systems are that they continue the trend of decreasing network losses and increasing supply source availability, however the mass flows required rise as well. Lund found that the increasing cost of the piping network combined with the higher capital costs at the customer negated the advantage of these systems over LTDH.

2.3.2 Prosumers

A prosumer is a utility customer who both produces and consumes energy, such as heat or electricity [18]. Prosumers are relatively common in electrical networks, where small installations of solar PV and other technologies allow owners to export energy to the grid during high production periods and import energy when needed. This type of interaction is not limited to small installations, as historically large industrial installations such as pulp mills have both exported and imported energy from the grid depending on operational and economic considerations[7].

Prosumer opportunities are gaining attention in heating networks as well, where district heat connected customers with excess heat could export this energy to the grid. Utilising existing waste heat in heating has been identified as a key opportunity to reduce the emissions and primary energy consumption from heating [24]. In the Swedish context Brange has evaluated several aspects of prosumers in a Malmö district [18]. It was found that while prosumers can supply a large fraction of a district's energy supply their highest capacity to export from the district is in the summer when heat demand in the network is lowest. Adrianto, based on earlier work from Sawalha, has also found that while heat recovery can be achieved with a high COP in Swedish grocery stores for self-consumption, the temperature

[7] Note that this is slightly different than self-consumption, where a generator consumes part of the power generated onsite to power auxiliary equipment but still primarily exports energy.

requirements for export to the DHN can render the practice uneconomical in some cases [49].

Stockholm Exergi's Open District Heat program allows customers to become prosumers or suppliers by selling their excess heat to the utility. Prosumers can supply energy to either the supply or return pipe, depending on the temperature level they are able to produce. Delivering to the supply pipe requires a delivery temperature of at least 68°C, while there is no temperature requirement to delivery to the return pipe. The program also offers two delivery models, call and spot. Under the call model participants must provide a certain heat power when requested with a guaranteed call below 12°C, while the spot model allows customers to deliver when they wish [50].

One common type of prosumer are owners of chiller systems, such as those installed in grocery stores, refrigeration warehouses, and ice rinks. Under standard operations the heat from the chiller is rejected to the ambient air, or using DCW as a heat sink in times of high outdoor temperatures [51]. This mode of operation is termed floating point condensing (FPC) mode.

Trans-critical CO_2 chillers have gained market share in recent years due to technological developments. This chiller cycle is especially useful in Nordic climes where summer temperatures rarely rise above 30°C, enabling rejection of heat with the use of only ambient temperature through much of the year [52]. However due to the nature of the refrigerant, relatively high pressures in the range 70-100 bar are required to achieve the condenser outlet temperatures required for operation. On the condenser inlet these high pressures can result in relatively high temperatures of up to 110°C, making these chillers an attractive source of waste heat. Heat recovery can be achieved by the addition of a desuperheater as seen in Figure 10 that transfers heat from the hot refrigerant to a heat sink, for example the district heating network.

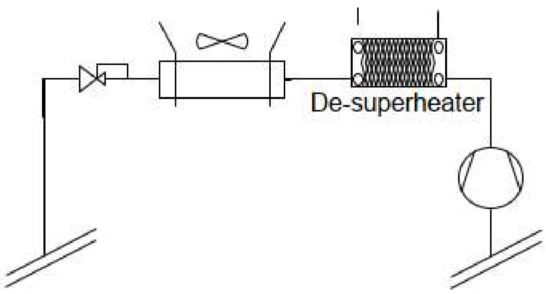

Figure 10: Heat Discharge/Recovery Arrangement for a Chiller [52]

2.3.3 District Cooling Networks

District cooling networks (DCN) provide the service of cooling in much the same way that DHN provide heating. Chilled water is distributed to DCN customers where it absorbs heat, thereby providing a cooling service. DCNs are identified by Lund as a component of 4GDH as they give access to a wider array of heat sources and sinks [12]. In addition to this service, which provides value in its own right, the energy that the DCN removes from customers can be utilised in the DHN if the temperature is increased through the use of heat pumps. Stockholm has the largest DCN in the world, with more than 250km of network [53], and so is able to make use of this energy when it is economically feasible. The collection of energy using the DCN and the availability of methods to reclaim this energy to the DHN also means that the DCN becomes an additional, lower, temperature sink for waste heat to be collected into. This service can be seen in the applications for refrigeration owners to become a supplier to the DHN, where a DCN connection provides a constant temperature cooler for existing chillers and the DHN is able to utilise the energy provided when economically applicable [51].

DCNs are able to reduce a district's electrical load required for cooling in two ways. First a DCN can make use of ambient cooling sources to dispose of heat, for example by cooling with sea water, rather than using an electrically driven chiller that would be utilised at the customer's site. Second, providing a constant low temperature source can improve the efficiency of many chiller systems, as it provides subcooling below the ambient temperature. This is particularly beneficial in trans-critical CO_2 chillers used in grocery stores and refrigeration warehouses [52]. Adding a sub-cooler after the air cooler, an extension of Figure 10, can substantially improve the COP of the chiller system by providing a lower return temperature prior to the expansion valve. This can be done either by utilising a heat pump or by connecting to a DCN if available, as is described in the Öppen Fjärrvarme handbook [51].

2.4 Electricity in LTDH

An important issue with the increasing use of electricity in heating are the emissions impacts of the additional electricity use, particularly in an interconnected market such as Europe where there is a wide variety of generation technologies. A common method in the literature is represented well by Brange [18], who compares emission production if the electricity production were to come from renewable generation, the Nordic residual mix, and marginal generation (presumed to be condensing coal power). This approach also used by Volkova in analysing the emissions of district heating when using grid power for heat pumps [41]. This method, while giving indication of emissions under different circumstances, does not capture seasonal or hourly production trends in the power system. Variations in the power supply are important when considering electricity use for heating as this is a highly seasonal demand.

To improve this method it would be ideal to know the emissions from electricity consumed at a given time, as well as the marginal emissions. The organisation Tomorrow has developed the open source Electricity Map [54], a live accounting of many region's specific emissions from electricity generation with a comprehensive overview of Europe. With this overview of electricity production Tomorrow is able to produce a hour by hour timeseries of the marginal emissions in a specific region, as well as the average emissions of electricity consumption in a region.

2.4.1 Average and Marginal Emissions

The average electricity emissions are the sum of all CO_2 emissions produced divided by the sum of all electricity produced in a given time period. The generation technologies in this average could produce a wide variety of emissions, but they are blended together to produce the average. The marginal electricity emissions are the change in emissions produced by a change in electricity consumption. Depending on the specific system the marginal electricity demand could be met by any number of flexible power plants, for example a hydropower generator or a condensing coal power plant. Measuring the marginal emissions allows for the analysis of the results of a specific action, such as turning on a heat pump, rather than the average effect of electricity use.

While the hydropower produces 99.0% of the marginal production within Sweden (from 98.3%-99.6% over the period Dec 1st 2018 to January 1st 2020) [55], as part of an interconnected electricity market Sweden can also import electricity from Finland, Latvia, Poland, Germany, Denmark, and Norway [56]. Each of these countries can in turn either produce their own power or import from their neighbours. As each of these countries has a distinct generation mix that is also influenced by long and short term weather patterns it is not a trivial problem to determine the marginal emissions in a specific region.

The organisation Tomorrow has developed the open source Electricity Map [54], a live accounting of regions' specific emissions from electricity generation with a comprehensive overview of Europe. With this overview of electricity production Tomorrow is able to produce an hour by hour timeseries of the marginal emissions of electricity consumption in a specific region, as well as the average emissions of electricity consumption in a region. As can be seen below in Figure 11 the emissions of marginal electricity consumption in Sweden is significantly higher than the average specific emissions, with the marginal consumption producing on average 254 g/kWh [57] as opposed to the average emissions of 49 g/kWh [58].

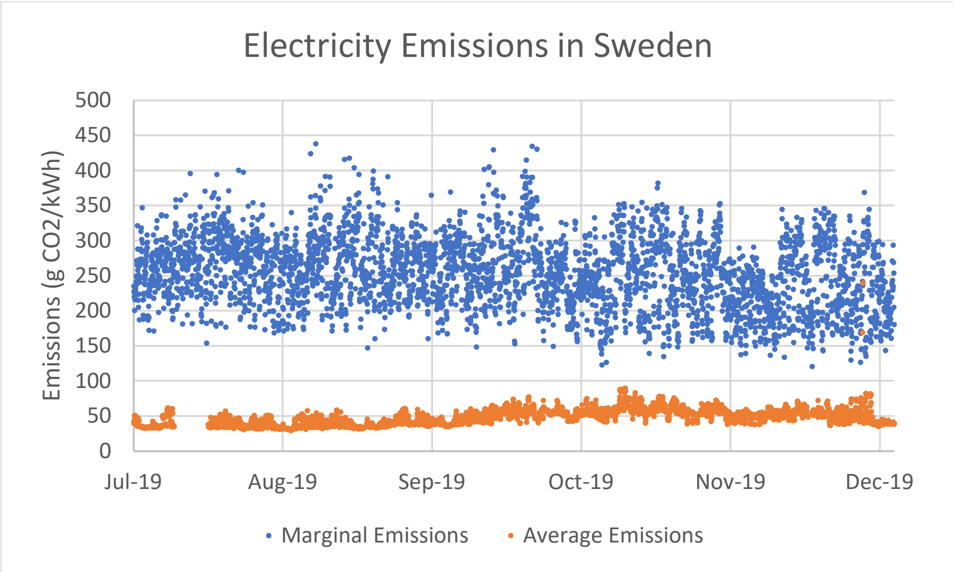

Figure 11: Marginal [57] and Average [58] Electricity Emissions in Sweden

Comparing marginal emissions as a multiple of average emissions it can be seen in Figure 12 that the marginal electricity production emits 1.3-12.7x more CO_2 than the average electricity mix (including imports) in Sweden at that hour.

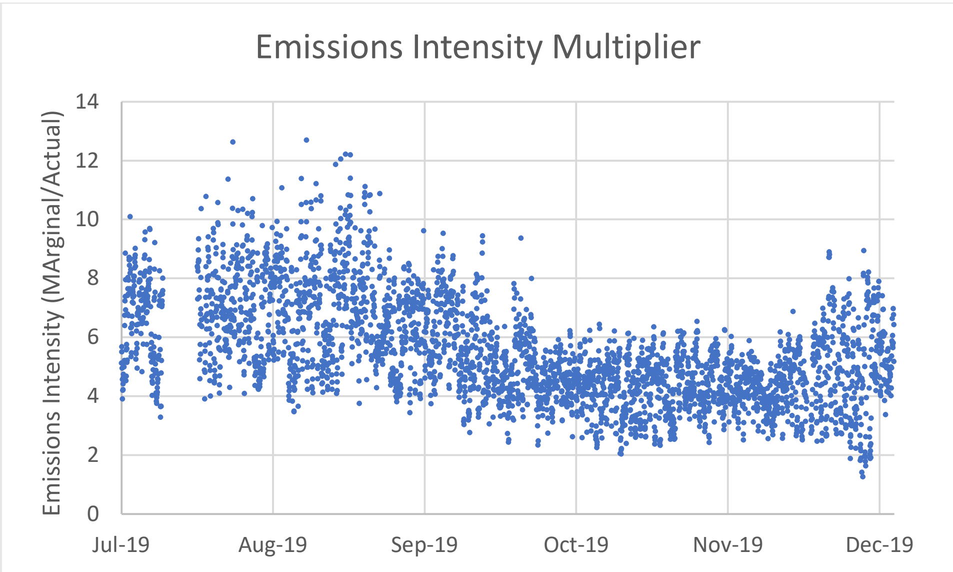

Figure 12: Emissions Intensity Multiplier, Marginal Emissions over Average Emissions

3 Case Study

The district of Loudden is part of the larger Norra Djurgårdstaden (NDS) development in Stockholm, one of the largest redevelopments of urban industrial lands in Europe. The Loudden district will be the last area to be developed within NDS, with construction targeted for 2025 and completion for 2030 [59].

Loudden is located on the coast of Lilla Värtan bay 2.0 km as the bird flies from Stockholm Exergi's, the DHN operator, main production facility Värtaverket and 2.3 km along roadways that are the likely route of the DHN. The district is also only a few hundred meters from the main return line to Värtaverket from the older districts in the center of Stockholm that form a large part of the DHN's energy demand. The proximity to the main return line would allow a short connection to supply high temperature return flow to the new district, and its location on the coast gives access to the water in the bay.

3.1 Loudden District Layout

The Loudden district, seen in Figure 13, is proposed to contain approximately 4000 apartments along with the services that a residential district requires. This includes grocery shops, office spaces, sports facilities, and schools [59]. Currently the district footprint contains three buildings whose footprints have been incorporated into the proposed layouts: two commercial buildings and a historical airplane hangar.

While firm development plans have not been approved, comparison with the previously developed districts in NDS [60], as well as architectural proposals [61], indicate that the residential buildings will likely be around 5 stories with a center courtyard. Similar to the northern districts of NDS the residences surrounding the courtyards will be around 12m thick. The two commercial buildings are two stories tall and will remain so, and the small building in the eastern square is proposed to be a small commercial space. While no path forward has been decided for the historical airplane hangar, it is proposed here that it would be converted into a sports facility.

The proposed district consists of 34 buildings containing 558,000 m^2 of floor area, of which 21,400 m^2 (3.8%) is commercial, 6,400 m^2 (1.1%) is sporting, and the remaining 530,200 m^2 (95.0%) is residential.

The proposed routing of the DHN in the Loudden district, shown as a blue line in Figure 13, is gathered from internal SE documents and will be assumed fixed.

Figure 13: Proposed Loudden Building Layouts with DHN (blue) overlaid on current OSM

3.2 Heat Demands

As a component of the sustainable urban living model proposed in the NDS development, the new buildings have a target energy use (electrical plus heat) of 50 kWh/m²/y. Starting from this base line, electrical consumption of 20 kWh/m²/y is removed leaving 30 kWh/m²/y available for combined SH and DHW use [59].

As discussed in Section 2.2: Building Heat Demands Sweden does not have a low energy building standard that would be sufficient to meet the energy use requirements set by Stockholms Stad for the Loudden district. The Danish Voluntary Low-Energy Class building standard of 2015 sets the heat demand for residential buildings at:

$$Q = 30 + \frac{1000}{A}\,\frac{kWh}{m^2y} \tag{1}$$

Where A is the heated area in m² of the building[8] [63]. This results in heat demand from 30.0-30.7 kWh/m²/y, with an average of 30.1 kWh/m²/y, for the new buildings in Loudden. With this target for context it can be seen how the nominal 4 kWh/m²/y DHW losses discussed in Section 2.2.2: Domestic Hot Water can become an important part of a building's energy performance.

Along with being a low energy demand district, the buildings in Louden will also be highly temperature efficient. To this end, the district heating building

[8] "Heated area" is defined as an area inside the building's thermal envelope that is temperature controlled to 10°C or higher throughout the year [62].

substations will be modeled as Russian 3-Stage connections as described in Section 2.2.6: Russian 3-Stage Substation.

3.2.1 Domestic Hot Water

As Stockholm's potable water is supplied by surface water from (Lake) Mälaren, the seasonal fluctuation temperature is important to determine the actual DHW demand. SE collects water temperature data from nearby Lilla Värtan during operation of the Ropsten heat pump facility, and in this work the temperature of Mälaren will be assumed to be equal. Using a reference incoming potable water temperature of 10°C [28] and a DHW supply temperature of 55°C it can be calculated that the DHW heat demand fluctuates approximately ±15% as seen in Figure 14, from 84.2% to 114.8% with an annual average of 102.2% of nominal. Social behavior influencing the consumption of DHW over the year was not considered. For a reference incoming water temperature of 10°C, DHW use in new buildings amounts to 13.9 kWh/m²/y. Accounting for the low average water temperatures identified in Figure 14 results in DHW use of 14.2 kWh/m²/y.

DHW losses in the buildings are taken at the recommended design value of 4 kWh/m²/y [36]. This sets a minimum summer demand from the district at 255kW.

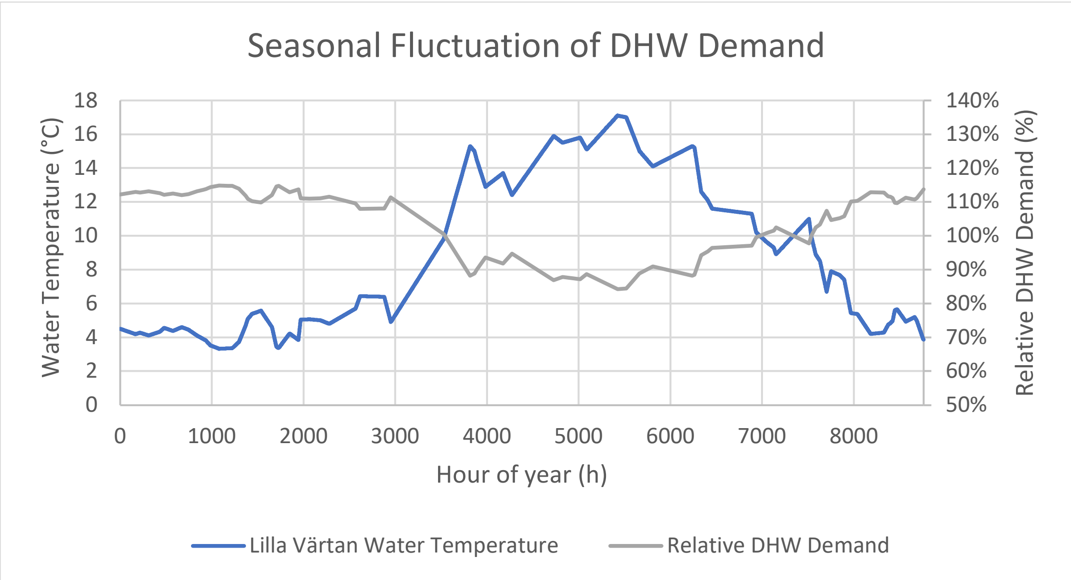

Figure 14: Seasonal Fluctuation of DHW Demand relative to 10°C reference water temperature.

3.2.2 Space Heating

The SH demands of the Loudden district are the remaining 16.2 kWh/m²/y after the reference DHW use is subtracted from the total heat energy budget.

3.3 LTD Network Design

The distribution network is implemented in a conventional tree structure, with a supply and return line. The peak SH and DHW demands of each building were determined, then each pipe section in the network was sized for the maximum downstream service requirements.

3.4 SH Peak Demand

The peak SH demand for each building was extrapolated from the PlanHeat results to the demand at the DOT of - 20°C. These results are seen in Figure 15.

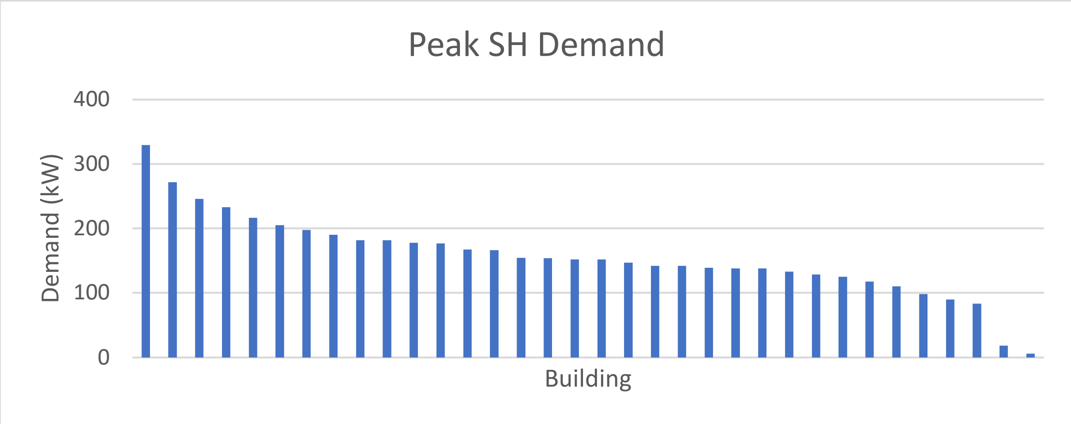

Figure 15: Peak SH Demands for the Loudden Buildings

3.4.1 DHW Peak Demand

As the peak DHW depends non-linearly on the number of apartments in a building, the 4000 apartments planned for the Loudden district [59] were distributed according to the available floor area into the 30 residential buildings[9]. The peak DHW demand (in kW) was determined for each building, seen in Figure 16, according to the formula below, where n is the number of apartments in the building [64]. It is noted that according to this formula the minimum DHW peak, that for only a single apartment, is 57kW.

$$P_{DHW} = 57 + 15.3\ \ln(n^3 - n^2 + 1)^{1.17} \tag{2}$$

[9]Dividing the 4000 apartments among the 530,200 m² of residential space, and presuming 80% of the floor area of each five-story building was utilised for apartments, gives an average apartment size of 106 m².

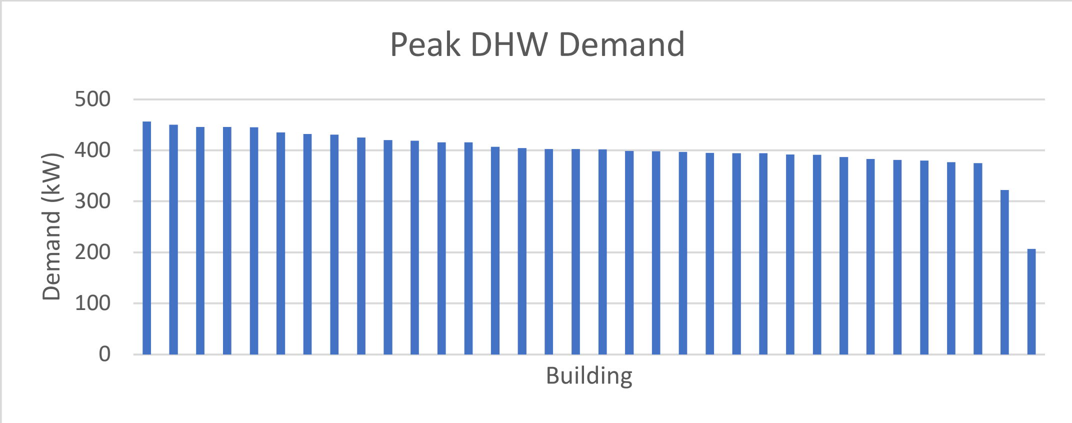

Figure 16: Peak DHW Demand for the Loudden Buildings

3.4.2 Dimensioning the Network

With the peak SH and DHW loads for each building in hand, the peak downstream demand at each node was calculated. At each node the peak downstream SH and DHW demands were evaluated then compared to determine the dominant service. An interesting result of installing high efficiency construction is that the DHW remains the dominant heat demand for many more apartments than with conventional construction, as seen in Figure 17. In older construction (where the SH demand at DOT is much higher than in new construction) the peak SH demand, which depends linearly on the number of apartments, rises much more quickly than in newer construction. As noted earlier, the peak DHW demand for a small number of apartments is higher than the peak SH requirements. Thus, we see that for older buildings requiring 6 kW of SH at DOT per apartment, DHW remains the dominant service until more than 56 apartments. In new construction requiring less SH at DOT the DHW service remains the dominant service until 530 apartments. As a reference, the high efficiency buildings in Loudden require on average 1.24 kW of SH at DOT per apartment, making SH the dominant service for more than 410 apartments.

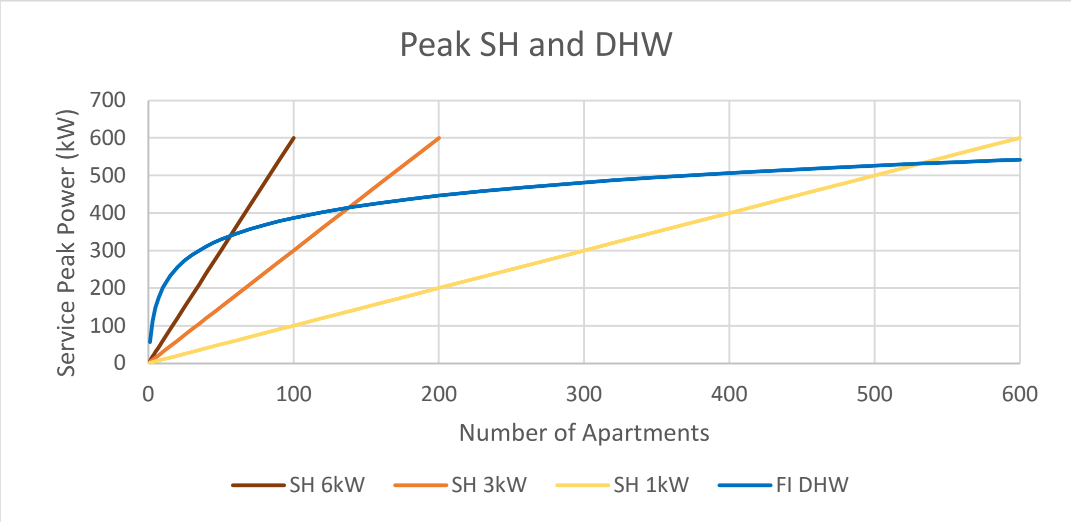

Figure 17: Comparison of SH and DHW demands for different constructions

The pipes were dimensioned with a maximum pressure drop of 0.2 bar/km (200 Pa/m) and using plastic pipes, the use of which in LTDH is discussed in Section 2.3.1: Low Temperature District Heating. The mass flows required for the SH demands were evaluated at a supply temperature of 65°C and a return temperature of 43°C, assuming a 60/40 secondary SH schedule and a primary return 3°C above the secondary return operating at DOT. The mass flows for the DHW demands were calculated again for a supply temperature of 65°C but with a return temperature of 29°C, simulating the summer peak demand where the primary return temperature is 12°C above the incoming water temperature of 17°C. The supply and return networks have the same pipe diameters throughout. In addition, the 3rd pipe network has the same diameters as the return network[10].

Detailed ground temperature measurements are difficult to obtain, but a correlation to air temperature used in the case study of another Stockholm neighbourhood can be seen below, where T_g is the ground temperature and T_a is the air temperature [47]:

$$T_g = \begin{cases} T_a \leq 0, & 5 \\ 0 < T_a < 20, & 5 + \dfrac{T_a}{2} \\ T_a \geq 20, & 15 \end{cases} \qquad (3)$$

[10] There are many uncertainties surrounding the flows in the 3rd pipe, and so as a simplification the diameters were matched to the return line to allow the maximum flow to be accommodated. A methodology for dimensioning of a 3rd pipe network could be the object of future work.

To account for the thermal mass of the ground these temperatures were converted to an effective ground temperature using a rear facing 7 day rolling average, seen in Figure 18.

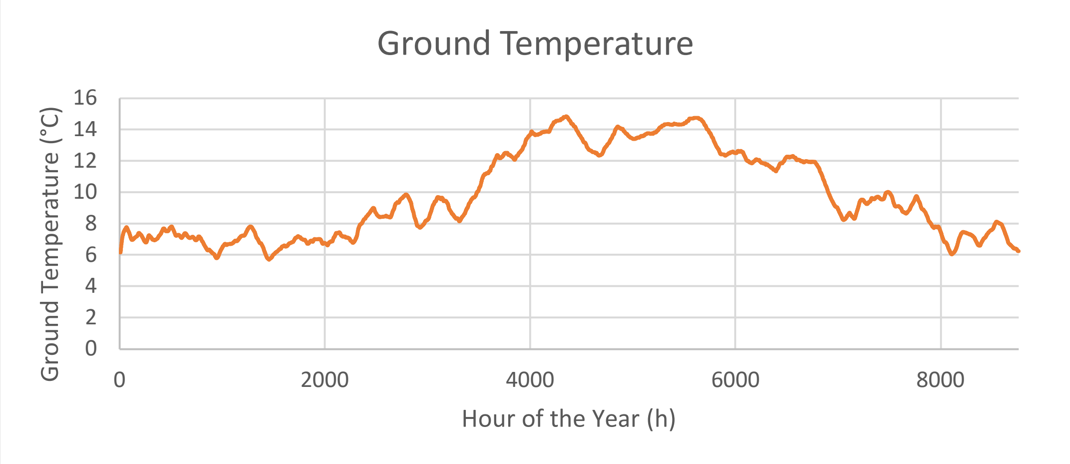

Figure 18: Modeled Ground Temperature in Stockholm 2020

3.5 DHN Production and Emissions

Like many DHN, the network serving Stockholm uses several heat supply and fuel combinations depending on the demand for heat and the market price of electricity. A simplified merit order for the Stockholm DHN is seen below in Figure 19. Currently the demand is dominated by SH. There is a linear dependency between this SH demand and the outdoor temperature below 16°C. At temperatures above 16 °C heat is supplied almost entirely by waste heat recovery with a small amount from DCN heat pumps. This share mostly corresponds to DHW heat demand.

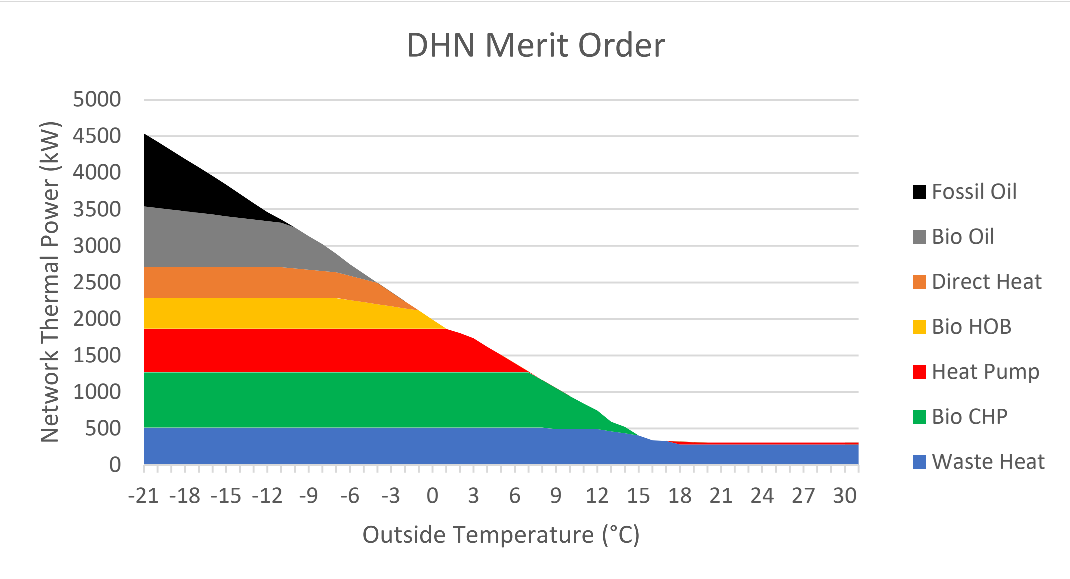

Figure 19: Stockholm DHN Merit Order

The short term marginal emissions of each technology are shown below in Table 2. Determining the marginal emissions of a heat generating technology is a complex question, particularly in a DHN using biomass fuels within an open electricity market. The short term marginal emissions should answer the question "What is the change in emissions if heat demand is increased now?". This question is more straightforward when discussing fueled boilers, but still some clarifications must be made. Biogenic emissions from the solid and liquid biofuels are counted as carbon-neutral in this work. The LCA fossil emissions of these fuels and technology combinations are collected from [65] and [66].

Table 2: Short Term Marginal Emissions Factors

Technology	Factor (kg/MWh_{th})
Waste Heat CHP	0
Solid Biofuel CHP	17
Heat Pump[11]	12
Solid Biofuel HOB	17
Direct Heat[12]	0
Liquid Biofuel HOB	24
Fossil Oil HOB	276

The waste heat sources in the Stockholm DHN are dominated by municipal solid waste (MSW) incinerators with CHP capability. While CO_2 emissions from Swedish MSW incineration are 41% of fossil origin [67], the incineration of waste will continue at the same rate regardless of the DHN heat recovery demand as the primary service of a waste incinerator is waste incineration. For this reason, the short term marginal emissions of heat recovery from WtE plants will be 0 kg/MWh. This does not minimise the discussion surrounding the committed emissions of new WtE plants, however this is beyond the scope of this work.

A similar argument is applied to the Direct Heat generation. As the CHP plant is nominally producing both heat and electricity, the decision to cease production of electricity in favour of heat does not change the amount of fuel entering the boiler but only the division of heat generated in the boiler. As

[11] For 2019/2020 Swedish average grid power (43.4 g/kWh [58]) and a HP COP of 3.5

[12] Direct Heat is the practice of diverting steam from the turbogenerator to a condenser in order to generate heat at the expense of producing electricity.

there is no change in the amount of emissions in either the CHP or Direct Heat case, the short term marginal emissions will be 0 kg/MWh.

The emissions of heat generated from heat pumps will depend on the emissions generated in producing the electricity and the COP of the heat pump at the operating conditions. Taking into consideration the Swedish average and marginal electricity emissions data from Tomorrow discussed in Section 2.4.1: Average and Marginal Emissions as well as the emissions factors in Table 2 an average specific emissions curve can be developed for the Stockholm DHN merit order. Seen below in Figure 20 the specific heat emissions are shown with 95th/5th percentile bounds, as well as a reference for CO_{2e} emissions for electricity from new wind generation (11 g/kWh [56]).

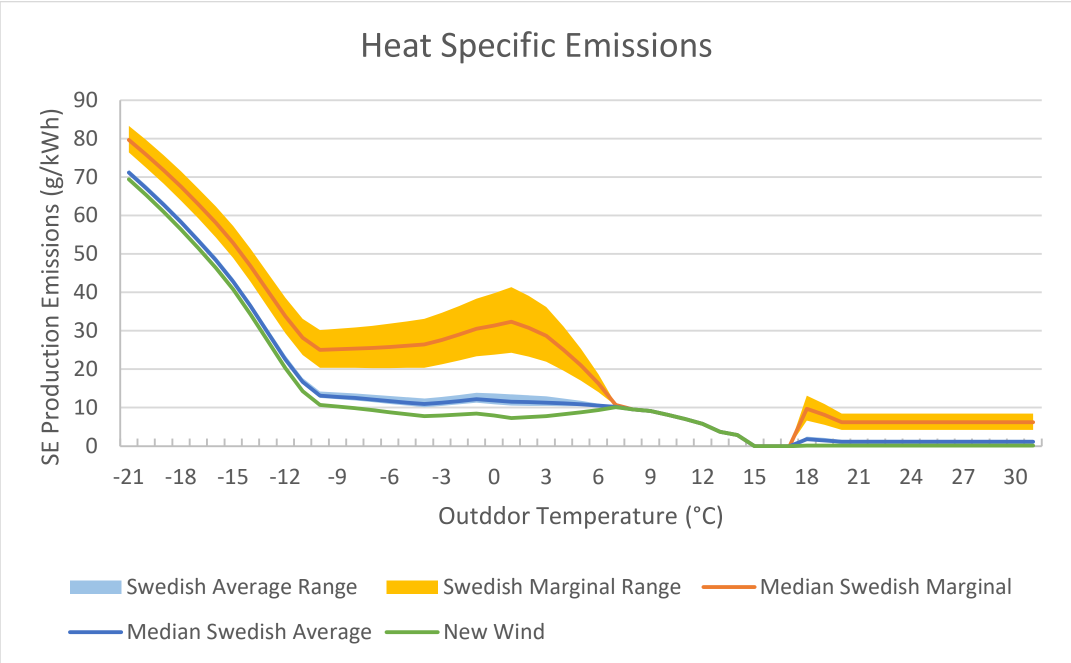

Figure 20: SE Heat Specific Emissions considering emissions from consumed electricity

3.6 Outdoor Temperatures

Stockholm has a 1961-1990 historical average of 4040 HDD_{17}. 2020, the year for which data was provided in this case study, as was a warm year relative to the historical average in Stockholm with 2901 HDD_{17} [68] or 39% fewer than the historical average. The temperatures ranged between -3.8°C and 29.7°C, as seen in Figure 21 [69]. The Swedish Meteorological and Hydrological Institute (SMHI) has estimated that under future IPCC climate scenarios Stockholm's annual heating requirements will decrease to a median of 3350-3360 HDD_{17} in the period 2011-2040, a 17% decrease from the period 1961-1990 [70].

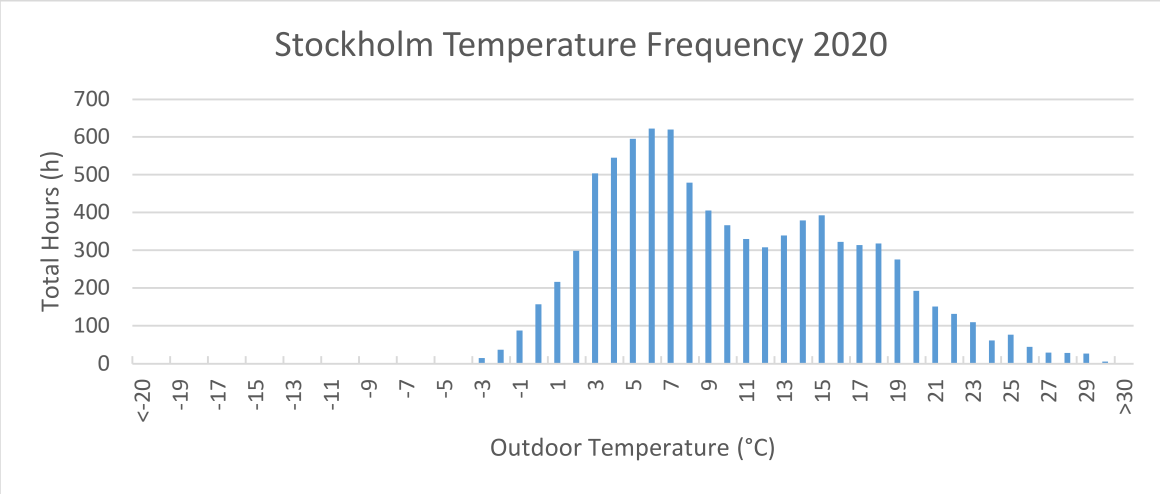

Figure 21: Stockholm Outdoor Temperatures 2020

While 2020 was an exceptionally warm year for Stockholm even considering the expected climate change to 2040, it is still relevant to the broader Swedish DHN context. The city of Malmö, in southern Sweden, is expected to see a change from a historical average of 3260 HDD_{17} to a median of 2570-2610 HDD_{17} in the period 2011-2040 [70], a range which Stockholm's 2020 fits well within.

3.7 Network Temperatures

The section of the HTN that the new district would be adjacent to operates with a typical 3GDH temperature profile, as seen in Figure 22 below. The supply line operates at an annual time weighted average of 80.4°C, with a 99th percentile high of 92.2°C during the heating season and a 1st percentile low of 67.7°C during the summer season. The return line has an average temperature of 41.4°C, with a 1st percentile low of 35.5°C and a 99th percentile high of 52.0°C during the summer season. A clear seasonal pattern is evident in both supply and return temperature profiles, highlighted in Figure 23, with the high summer return temperatures in particular illustrating on a network scale some of the difficulties discussed in Section 2.2.3: Customer Substations.

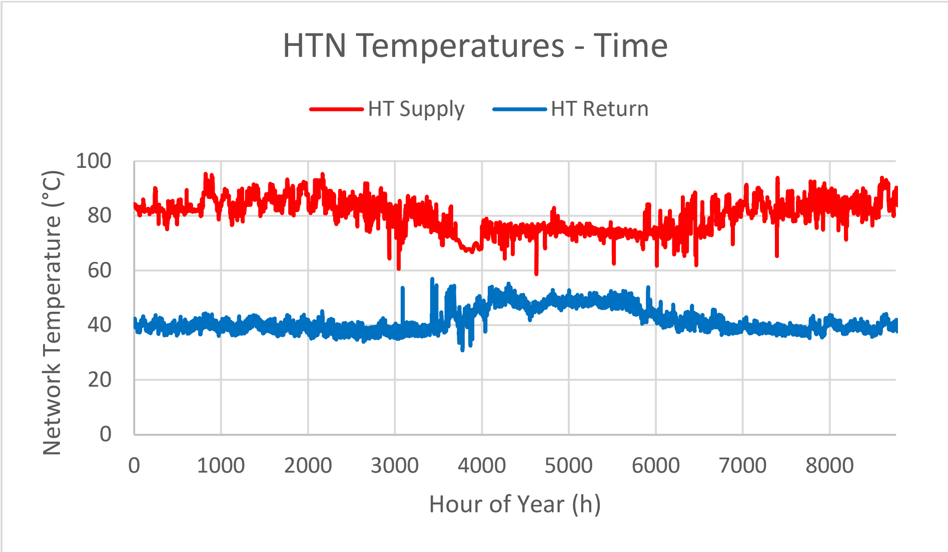

Figure 22: HTN Supply and Return Temperatures for 2020

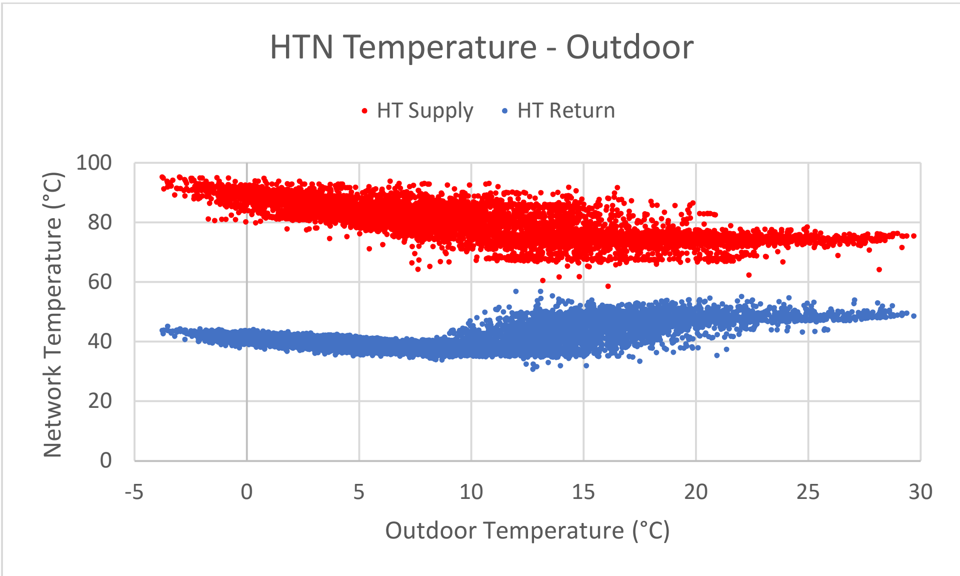

Figure 23: Outdoor Temperature dependance of HTN Supply and Return Temperatures

4 Scenario Descriptions

Five scenarios are developed exploring how heat could be supplied to a new LTD with a DHN solution and how these solutions would interact with the existing DHN. It is presumed that each of the solutions will service the same new district with low demand and highly temperature efficient buildings. An overview of the five scenarios is given in Table 3, with details in the sections below.

Table 3: Scenario Overview

Name	Variations	Heat Sources	Supply Temp.	Export[13]
S0: High Temperature Supply	a) Single Return b) With 3rd Pipe	HT Supply	High Temp.	-
S1: Utilising HT Return	a) Single Return b) With 3rd Pipe	HT Supply HT Return	Low Temp.	-
S2: Utilising a Waste Heat Source	a) Single Return b) With 3rd Pipe	HT Supply Waste Heat Flow	Low Temp.	-
S3: Electrifying the LTD	a) Single Return b) With 3rd Pipe	HT Return Sea-Source HP	Low Temp.	No
S4: Prosumers in the LTD	a) Deliveries to LTS b) Deliveries to LTR	HT Supply HT Return Prosumer Deliveries	Low Temp.	Yes

Each of the scenarios will be connected to the high temperature DHN supply to serve as a backup supply, if not as part of the main heating system, as well as a heat only unit to serve as a source of last resort. In each scenario the LT

[13] S0, S1, and S2 have no in-district generation and so can no export. The heat pump in S3 could export to the wider grid, but is not connected in a manner that would allow it to do so. In S4a excess heat can be exported to the existing network and in S4b the heat must be exported to the existing network as it is delivered to the return line.

return line is kept separate from the HT return line. This is to leave open the use cases for this new temperature level, the potential of which is explored further in Section 6.2.1: Description of Heat Recovery Bands. As well, each scenario supplies the building substation with a single supply line and a single return line, that is a single supply temperature is provided for all the building's heating demands. In the figures below the LTD is shown as a single entity, but as described in Section 5.2: Network Model each of the building blocks is modeled separately.

4.1 Scenario 0: High Temperature Supply

In S0, seen in Figure 24 below, the new LTD is supplied by the existing HT supply line at the temperatures used to serve the rest of the network (seen in hourly timeseries in Figure 22). This scenario is intended to serve as a baseline on how a LTD would perform if supplied by the existing HT DHN. Within studies of 4GDH it is important to separate the effects of a low demand, highly temperature efficient, district from the effects of the LTDH as they are frequently used together. This baseline approach has been taken in several studies, and especially when utilising temperature cascades as Köfinger did for a refurbished district in Vienna [40].

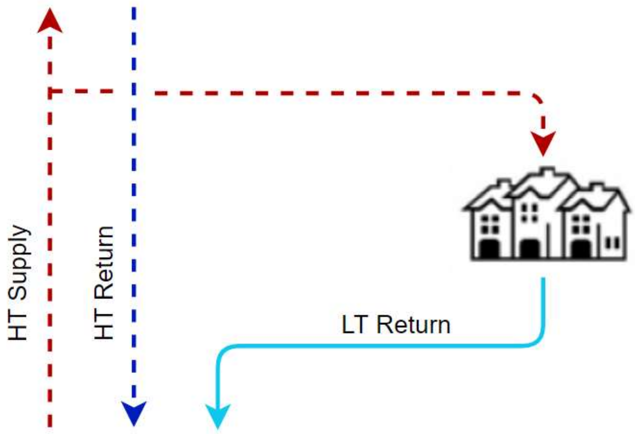

Figure 24: S0 High Temperature Supply

4.2 Scenario 1: Utilising HT Return

A mixture of the HT Return and HT Supply flow is combined, seen in Figure 25, to provide the LT Supply flow to the LTD at a year round temperature of 65°C and the flow rate that the LTD demands. This takes advantage of the heat remaining in the HT Return that can be used to heat the LTD. This is an example of an energy cascade that has been utilised on a district level in DHN as temperature levels have decreased over time. This arrangement allows districts that require higher supply temperatures and heat transfer rates to continue to receive those conditions while also making use in new or renovated districts of the benefits that LTDH can provide.

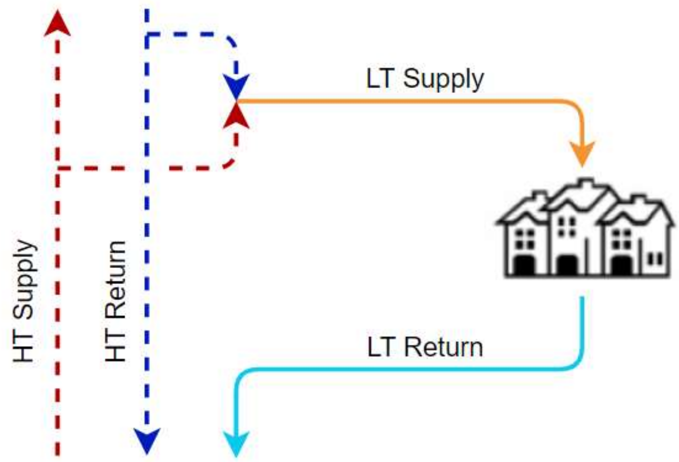

Figure 25: S1 Utilising HT Return

4.3 Scenario 2: Utilising a Waste Heat Source

A waste heat source stream is introduced that can provide a midrange temperature between the HTS and HTR, in this case envisioned at 60°C. The source of this waste heat flow is not identified in the scenario specifically, but it is imagined that it could come from a variety of sources available to a DHN. This might include a FGC, waste heat recovery from industry, or heat recovery from auxiliary cooling services in a CHP plant. A flow near 60°C could also be sourced from a heat pump with a cost effective COP, however this scenario assumes that there are no emissions production in the use of the waste heat source as would be the case with an electrically driven heat pump. The objective of this scenario is to explore the impact of several opportunities available to the DHN operator that, while attractive, do not quite create temperatures high enough for supply of the LTD (65°C in this case) alone and so require some HT Supply flow to increase the temperature as seen in Figure 26.

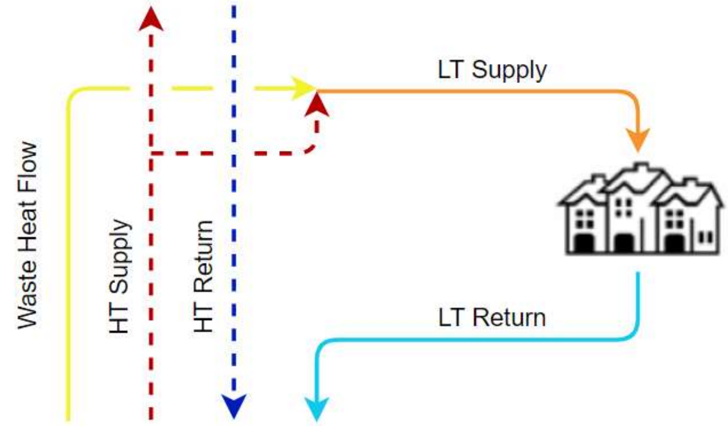

Figure 26: S2 Utilisation of a Waste Heat Flow

If a LTD was near an area that had significant 3rd pipe recirculation flow, this could also serve as the starting point for a supply stream to a LTD. It is not envisioned that all LTDs could utilise 3rd pipe flow, but that 3rd pipe flow from a larger collection of districts could be collected to serve a single district.

4.4 Scenario 3: Electrifying the LTS

A sea-source heat pump is used to provide energy to the LTD increasing the temperature of the HT Return, as seen in Figure 27, to the required 65°C. Similar technology is already utilised in many DHN but not as the primary means of supplying a LTD. The lower supply temperatures of LTDH make it possible to reach the supply temperature with a heat pump alone. This scenario mirrors the equipment in the 215 MW_{th} Ropsten heat pump installation on the same bay [71] that supplies heat to Stockholm's DHN prior to the boilers, albeit much smaller.

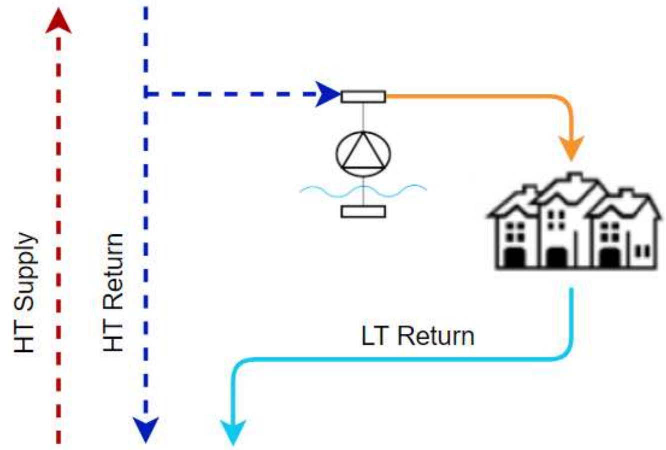

Figure 27: S3 Electrifying the LTD

Utilising large heat pump such as described here is a common method of electrifying heating in cities with DHNs. Many arrangements have been described including from a warm waste water effluent source [47], from geothermal sources, from industrial waste heat, and from sea water as described here [17].

One of the reasons that it can be difficult for a heat pump to serve as the peaking supply in DHNs, besides the high temperatures that can be required, is that there is a seasonal change in the required supply temperature that can be difficult to incorporate efficiently into the HP design. This is not the case in LTDH with a constant supply temperature throughout the year, as the supply temperatures are dominated by the DHW service.

4.5 Scenario 4: Prosumers in the LTN

In this scenario third party participants are able to add heat to the network, introducing prosumers and a move to decentralised production. This scenario is built to examine the impacts that a concept like Stockholm Exergi's existing Öppen Fjärrvarme program [50] would have in a LTD, as well as to explore localised heat production. It is important to note that in this case the LTD is still connected to the larger DHN through the supply and return lines, and this local heat production is not intended to create an islanded system.

This scenario has two arrangements. In both arrangements flow is taken from the LT return line and waste heat from the prosumer's chillers is recovered in a de-superheater. In S4a, seen in Figure 28, prosumers deliver heat at a temperature of 68°C, the minimum specified by Stockholm Exergi's current Öppen Fjärrvarme offering [51], and the flow is sent to the LT supply line. As the prosumer supply temperature T_{PRO} is higher than the LT supply temperature throughout most of the year this practice offsets heat and flow demand from the HT supply line.

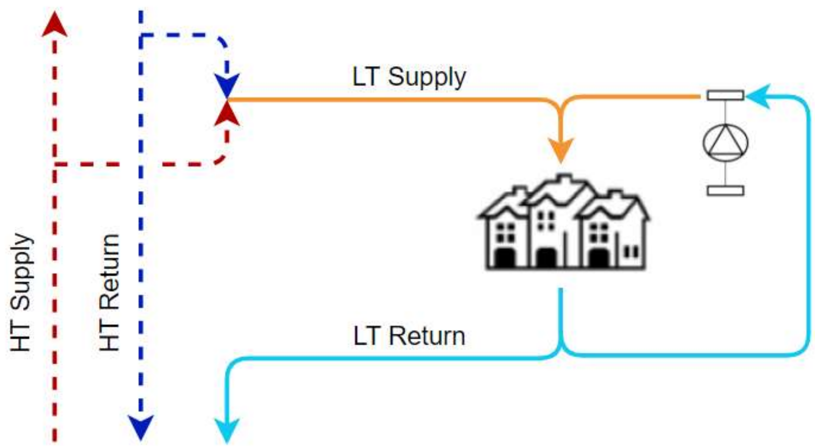

Figure 28: S4a Prosumers to the LTS

In S4b, seen in Figure 29, the prosumer adds heat at the temperature most convenient to chiller arrangements that are not designed to deliver to the DHN and the flow is sent to the LTD return line. The convenient temperature is estimated to be 45°C, as this is the minimum temperature that a chiller would have to produce to discharge to ambient conditions throughout the year.

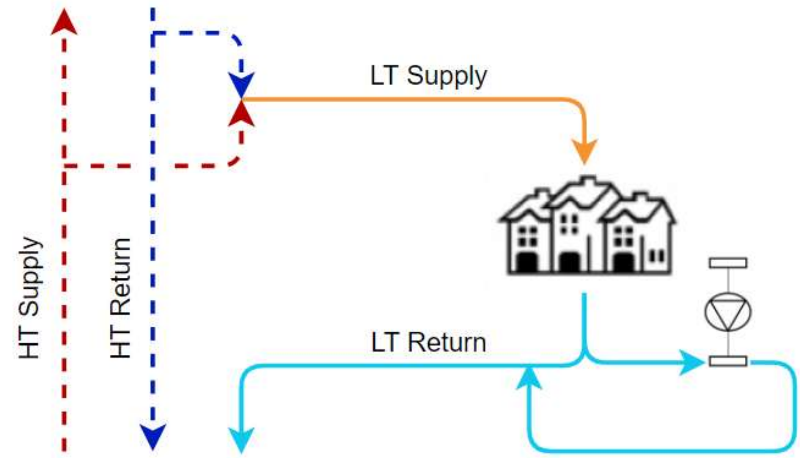

Figure 29: S4b Prosumers to the LTR

These scenarios will investigate a contradiction sometimes seen in distributed heat production proposals for 4GDH. Whereas one objective of 4GDH, and LTDH particularly, is to lower the return temperatures, these same low return temperatures are enticing to use to collect energy from novel sources.

4.6 3rd Pipe Arrangements

Scenarios 0, 1, 2, and 3 are implemented a) conventionally with only a supply and return line and b) with a 3rd pipe[14]. Seen in Figure 30, this 3rd pipe acts as a second return line and is utilised to divert "hot" return flow that increases the temperature of the primary return line. Flow is diverted on a substation-by-substation basis into this 3rd pipe when the return temperature is above a certain temperature or if bypass flow is required in the network to maintain supply temperature levels. These scenarios will evaluate the effects that a 3rd pipe has on LT return line temperatures and the heat losses on the return side of the network.

[14] The three pipes are the LT supply line, LT return line, and the imaginatively named 3rd Pipe return line

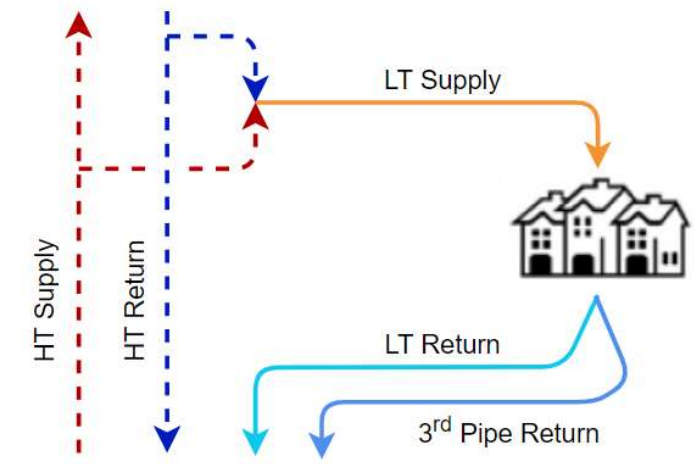

Figure 30: S1b Utilising HT Return with 3rd Pipe

5 Modeling

The modeling of the scenarios, seen in Figure 31, was performed in the Python environment. The pipe network modeling tool PandaPipes was used to determine that physical parameters in the network and the PuLP linear optimiser to determine the heat supply sources for the network. The district's hourly heat demands were determined by PlanHeat after modeling the district's buildings in QGIS. Hourly data regarding the HT network variables was supplied by Stockholm Exergi and hourly electricity emissions data by the organisation Tomorrow, both for the year 2020.

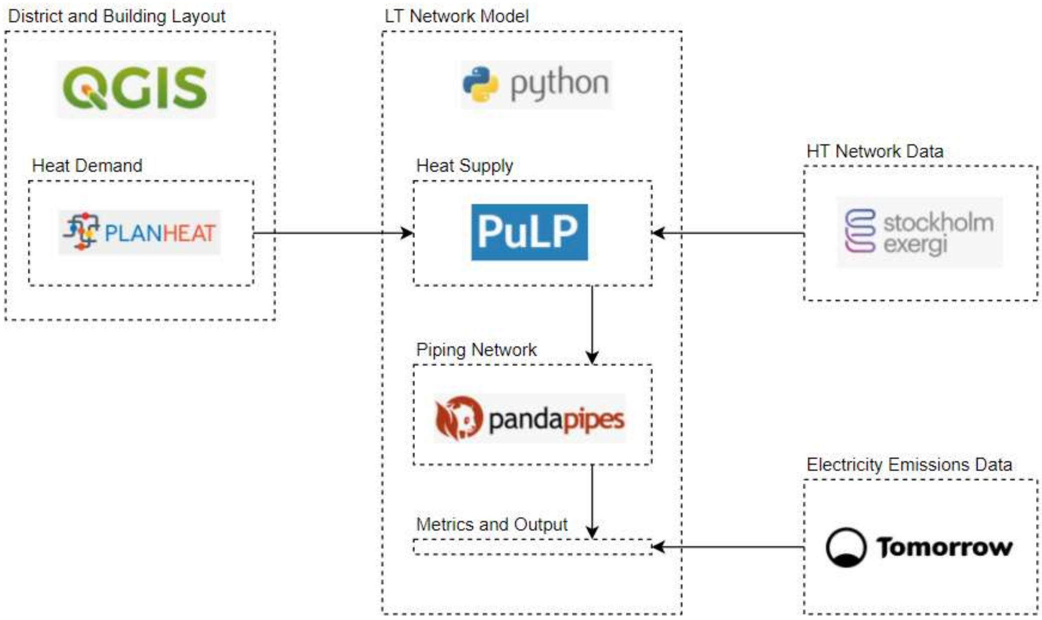

Figure 31: Modelling Workflow

5.1 Tools

Each of the tools utilised is free and open source.

5.1.1 QGIS

QGIS is an open source geographical information system developed by the Open Source Geospatial Foundation that allows the user develop maps containing objects, layers, and base maps [72]. It can be used to overlay new objects, such as building polygons or district heating lines, on existing maps to produce geographical data about their location, area, or length as well as a visual overview of the area.

5.1.2 PlanHeat

PlanHeat is a plugin developed in the Python environment for QGIS. The tool allows the user to model the heating and cooling demands as well as network and individual supply scenarios for areas ranging from a single building to a city. PlanHeat also utilises several data bases to estimate local heating and cooling supply potential from a variety of sources including waste heat, biomass, geothermal, solar thermal, and surface water [73].

The tool consists of several modules that can be used alone or in combination depending on the desired output, as seen in Figure 32. PlanHeat allows the user to model heat demand using a top down "City" or bottom up "District" methodology. The City approach uses information such as population density, zoning, aggregated energy consumption to produce annual summaries useful for policy development. The District approach uses building specific information to determine an hourly output more useful for detailed energy system planning [73]. Only the District Mapping module was used in this work.

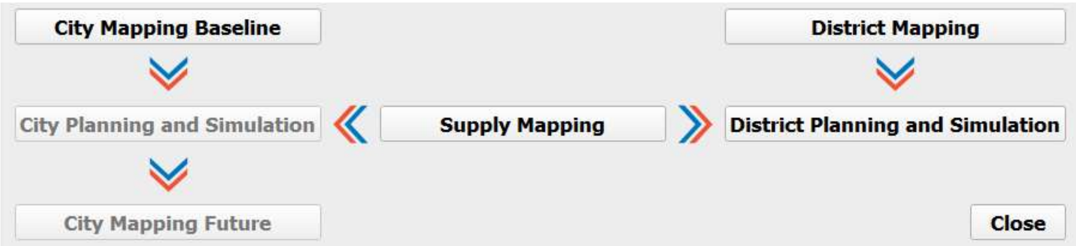

Figure 32: PlanHeat Module Arrangement

PlanHeat develops a building's heating demand based in its footprint from QGIS and user provided information including the year of construction, country, height, and use. The SH, DHW, and space cooling demand in hourly increments for a reference year for each of the buildings in the analysis are saved to a CSV. This file can be used directly as an output or as an input to further processing in the PlanHeat simulation module.

5.1.3 PuLP Optimiser

The PuLP Optimiser is implemented in the Python environment and is a linear optimiser capable of solving mixed integer problems. PuLP's capabilities can be added to any Python file. PuLP solves a linear optimisation problem according to the specified objective function and subject to constraints [23].

5.1.4 Pandapipes

Pandapipes is a python library that allows for the development of pipe networks with liquid and gas fluid flow by linking components together. From a set of initial conditions the state of the network can be solved for in terms of mass flow, temperature, and pressure. Pandapipes is built from the same architecture as the better known pandapower. Pandapipes performs a quasi-static state evaluation of the network, first evaluating the hydraulic parameters of mass flow and pressure then evaluating the temperature distribution in the network [21].

The components used in this work are described below .

- A Junction is a point that can connect other components. The parameters calculated at a junction are the temperature and pressure. One or many others components can be linked to a single junction.
- A Pipe is described by its length, diameter, interior roughness, linear heat loss coefficient, and external temperature. The mass flow through the pipe as well as the pressure and temperature loss through the pipe are calculated. A pipe is connected with a “to” and “from” junction. A pipe can be broken into segments to improve the calculation accuracy.
- An External Grid allows for a point of fixed temperature and/or pressure. Either the temperature, pressure, or both can be set. An external grid is located at a single junction.
- A Source allows for mass flow to enter the model, and the mass flow is fixed. A source is located at a single junction.
- A Sink allows for mass flow to leave the model, and the mass flow is fixed. A sink is located at a single junction.
- A Heat Exchanger allows for energy to be added to or removed from a flow without affecting the mass flow rate. A heat exchanger has a “to” and “from” junction to locate it in the network. The temperature on each end of the exchanger is calculated.

To completely specify the parameters of an individual flow, an external grid and a source or sink can be connected to the same junction. The external grid can specify the temperature and pressure while the source or sink can specify the mass flow.

Using pandapipes in a model can be broken into two stages: building and running the model. Building the model involves creating the components and linking them together. Running the model involves setting the initial conditions at the external grids, sources, and sinks then running the model to determine the final state of the network. Once complete, the temperature and pressure at each junction as well as the mass flow through each pipe and at each source and sink can be accessed.

5.2 Network Model

The DHN model comprises of a separate pandapipe network for each of the supply, return, and 3rd pipe systems (depending on the scenario). Each of the networks takes the same path shown in Figure 13 above. This path is divided into individual pipes. The supply network is implemented with a sink at each of the building blocks (BB) as seen in Figure 33. Each scenario has a different “supply end” (which would connect on the left of Figure 34) of the supply net, the details of which will be discussed in later sections.

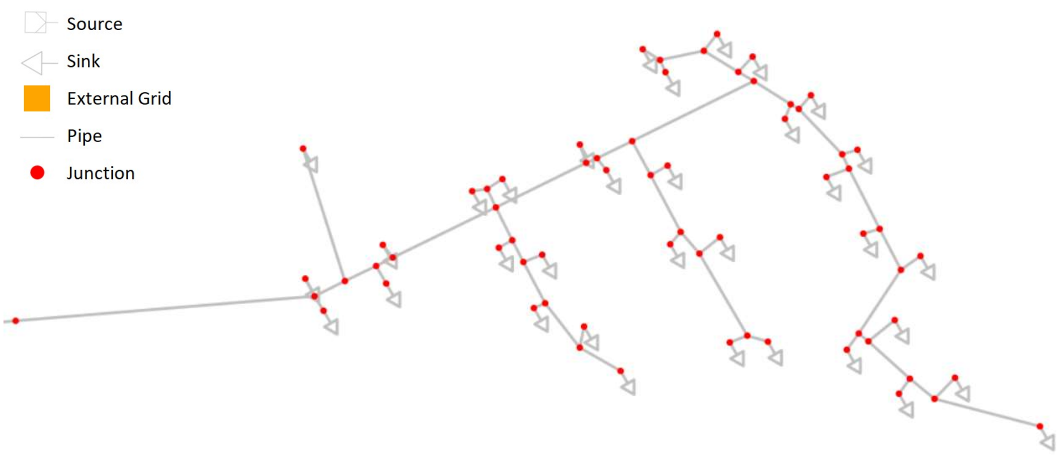

Figure 33: Pandapipes model for Supply Network to Loudden district

A useful arrangement is the fully specified piping connection seen in Figure 34. It contains an External Grid component specifying temperature and pressure and a Source component specifying mass flow. Both are located at the same junction and connect to a pipe. This arrangement is used to specify the supply temperature and/or pressure as well as mass flow at a point. It is used for the supply lines from the external DHN as well as the return lines from the BB substations.

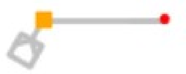

Figure 34: Fully specified source with temperature and/or pressure as well as mass flow

The return and 3rd pipe networks are arranged identically as in Figure 35, with the fully specified source of Figure 34 at each of the BBs and a common sink at the point where the district’s network would connect to the external DHN. The mass flows and temperatures at each BB are fixed, with these parameters cascading through the network. The pressure at the connection point is fixed, and the pressures throughout the rest of the network calculated.

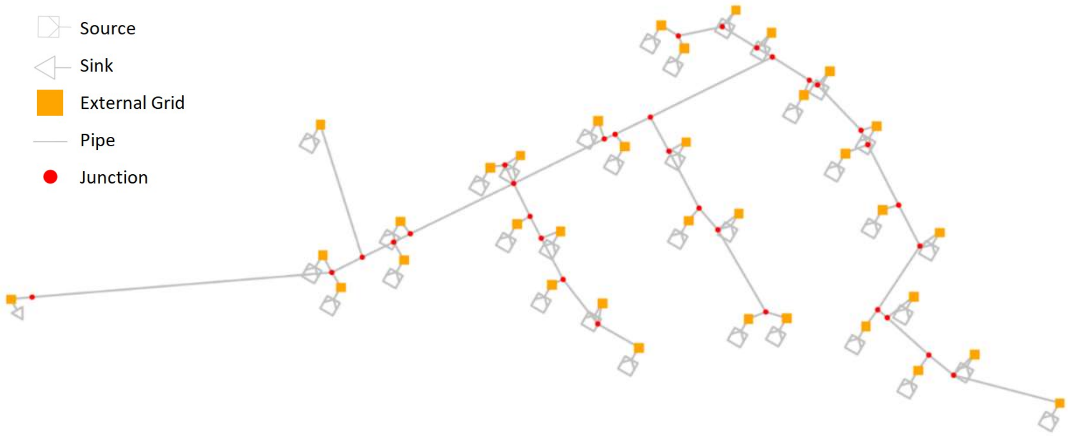

Figure 35: Pandapipes model for Return and 3rd Pipe Networks from Loudden district

The supply model for Scenarios 0, 1, and 2 is shown below in Figure 36, with the network and building blocks simplified for clarity. The three external sources can be mixed as needed to provide the required LTN supply temperature. The HT supply and return temperatures available to this district are drawn from real hourly data for the year 2020, while the Waste Heat flow has a fixed temperature of 60°C. Each of these flows have an unlimited mass flow available. Energy can be added in the Unmet Demand heat exchanger if the temperatures available in the sources are not sufficient to meet the target temperature. In addition to allowing for feasible solutions from the optimiser, the power and energy demand accrued by the Unmet Demand heat source indicates the characteristics of a local heat-only unit that may be needed in a given arrangement.

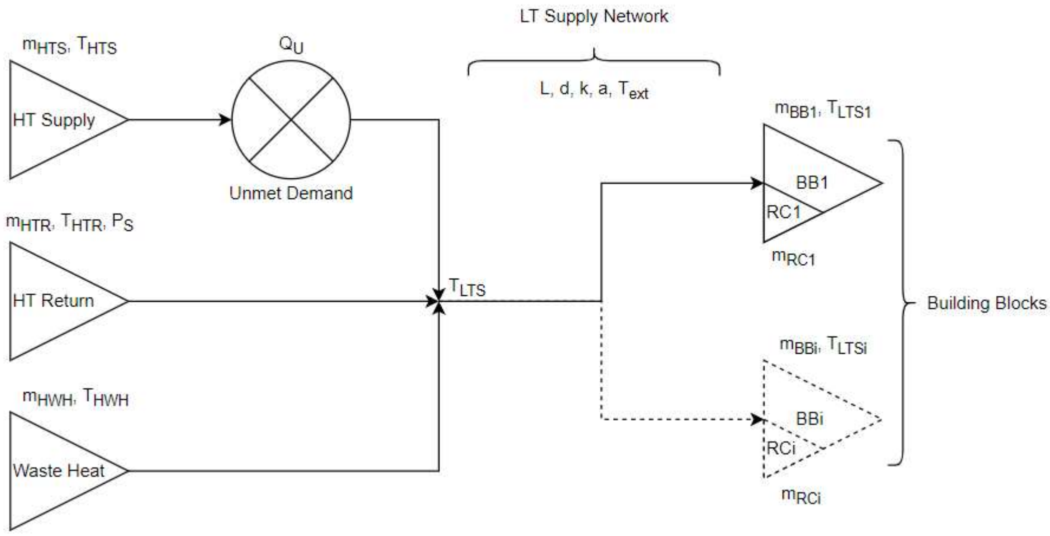

Figure 36: LT Supply pandapipes model for S0, S1, and S2

The PuLP optimiser determines the mass flow of each source, as well as any energy to the Unmet Demand heat exchanger, to satisfy the constraints below:

- The supply temperature must be satisfied

$$\frac{\dot{m}_{HTS}T_{HTS} + \dot{m}_{HTR}T_{HTR} + \dot{m}_{WH}T_{WH} + \frac{Q_U}{c}}{\dot{m}_{HTS} + \dot{m}_{HTR} + \dot{m}_{WH}} \geq T_{LTS} \tag{4}$$

- The mass flow demanded by the BBs must be provided

$$\sum_{i=1}^{BB} \dot{m}_{BBi} = \dot{m}_{LTS} \tag{5}$$

The mass flow at each BB is determined in two parts: first by the heat demanded by that BB in that hour, and second by the amount of recirculation required to maintain the supply temperature in that part of the network, as seen below. The mass flow required to meet the heat demand is determined according to the operation of the substation. This depends on the fluid temperature supplied to that BB and the return temperature produced by the BB's substation, subject to the SH and DHW demands as described in Section 2.2: Building Heat Demands.

$$\dot{m}_{BBi} = \frac{Q_{BBi}}{c\,(T_{LTSi} - T_{LTRi})} + \dot{m}_{RCi} \tag{6}$$

The DHN operator is typically obligated to provide a minimum temperature to the customer at their substation, 65°C in the case of Stockholm Exergi. To ensure this is the case, the LTD supply temperature (T_{LTS} at the mix point) is adjusted from a nominal level of 65°C to ensure that the temperature loss throughout the network is countered. As the fluid travels a different path at a different speed to each customer depending on their location and the network layout, each customer will have a different delivery temperature. This minimum delivery temperature at a customer is determined and the LTD supply temperature is adjusted based on the lowest delivery temperature. Thus, each customer will receive a primary side supply of at least 65°C.

In the case low heat demand in a section of the network, causing high heat losses, a high LTD supply temperature may be required to supply a minimum of 65°C to customers. To counter this each customer substation can induce flow by bypassing supply flow past the substation into the return grid. Increasing the recirculation flow reduces the transit time in the network and so the temperature losses. The recirculation flow is increased at the BB with the coldest delivery temperature if either of the following is true:

- There is Unmet Demand while the HT supply temperature is greater than LT supply temperature
- The LT supply requirement is more than 5°C above the target of 65°C

This functionality is included in all of the scenarios, as recirculating flow to maintain network temperature is a standard operating practice in DHNs. The increased measurement and control capability that would be required to bypass flow individually at each substation is one of the possibilities of increased digitisation, a hallmark of 4GDH.

Once the flow and temperature conditions have been determined in the LT supply network, the mass flows at each BB are transferred into the LT return network model, a simplified version of which can be seen in Figure 37 below.

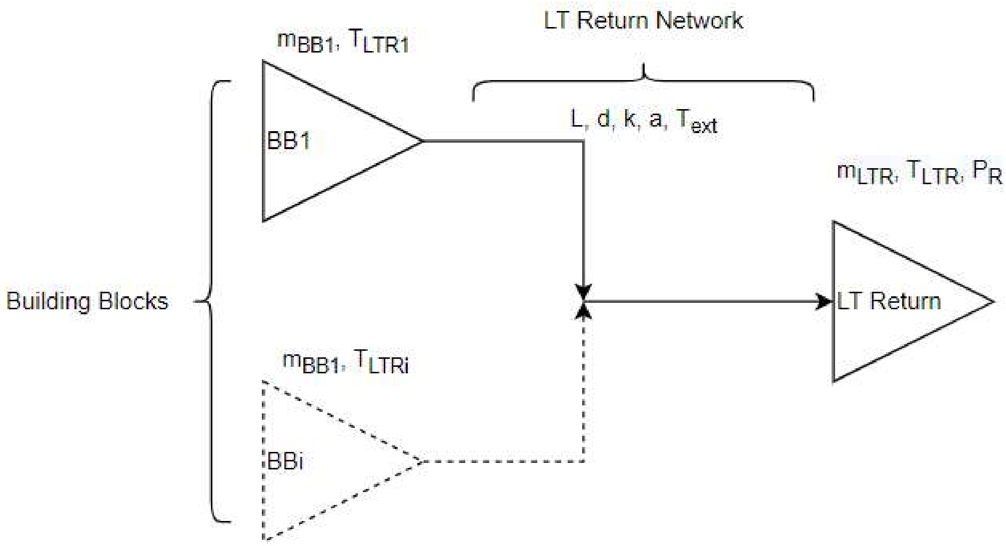

Figure 37: LT Return pandapipes model

5.2.1 Network Pump Power

Within a DHN pumps are used to move water throughout the network, and to provide a pressure difference across customers' substations. The amount of energy a distribution pump requires is based primarily on the pressure losses developed in the network.

The total pressure loss in the modeled system can be calculated by finding the BB with the lowest pressure in the LT supply network, adding the minimum differential pressure of 0.2 bar across the customer's substation [28], and adding the pressure losses from that BB through the LT return network. The higher pressure drops across the substations experienced at other BBs are consumed across the substation control valves and other equipment.

As one of the dominant themes of LTDH is an electrification of heating, and one aim of this work is to examine the electrical intensity of heating a LTD, any change in distribution pump electrical demand will have an impact on the electrical intensity of the heating system as a whole. Köfinger notes that modeling pump energy consumption is important to determine the electrical energy intensity of LTDH systems [40].

5.2.2 Emissions

The emissions caused by heating the LTD are calculated in two parts. The first part are the emissions from heat generation delivered from the existing DHN at that hour order as described in 3.5 DHN Production and Emissions. This is calculated with the production mix seen in Figure 19 and the methodology shown in Figure 20 considering the average electrical emissions in Sweden at that hour with data provided by the organisation Tomorrow. The second part is the emissions of electricity consumed directly in the LTN, either by network delivery pumps or HP in the scenarios, which is also calculated with the data from Tomorrow.

5.3 Implementation of Scenarios

5.3.1 Scenario 0: High Temperature Supply

In the baseline scenario only the HT Supply line is connected to the LTDHN, along with a heat-only unit characterised as a heat exchanger. In addition to the optimiser constraints noted above, the mass flows of the HT Return flow and Waste Heat flow are constrained to zero. The HT Supply temperatures are those of the Gärdet supply line for 2020 illustrated in Section 3.7: Network Temperatures.

A minimum delivery temperature of 65°C is maintained, although this limit is reached only in unusual circumstances.

5.3.2 Scenario 1: Utilising HT Return

The zero mass flow constraint on the HT Return flow is removed, and this flow is available at the temperatures in the Gärdet return line for 2020.

5.3.3 Scenario 2: Utilising a Waste Heat Source

There are no constraints on any of the three supply flows (HT Supply, HT Return, and Waste Heat Flow). The Waste Heat flow has a fixed temperature of 60°C and an unlimited mass flow available.

5.3.4 Scenario 3: Electrifying the LTN

A sea water source heat pump is connected to the HT return and waste heat source as seen in Figure 38 below. The heat pump will move ambient heat from the nearby Lilla Värtan into the LTDHN thereby raising its temperature to a point sufficient to supply the LTD. The electrical power of the heat pump E_{HP} is added as an optimiser variable, as seen below. The COP of the heat pump is calculated prior to the optimiser running to keep the problem linear.

$$\frac{\dot{m}_{HTS}T_{HTS} + \dot{m}_{HTR}T_{HTR} + \dot{m}_{WH}T_{WH} + \frac{Q_U}{c} + \frac{E_{HP} * COP}{c}}{\dot{m}_{HTS} + \dot{m}_{HTR} + \dot{m}_{WH}} \geq T_{LTS} \qquad (7)$$

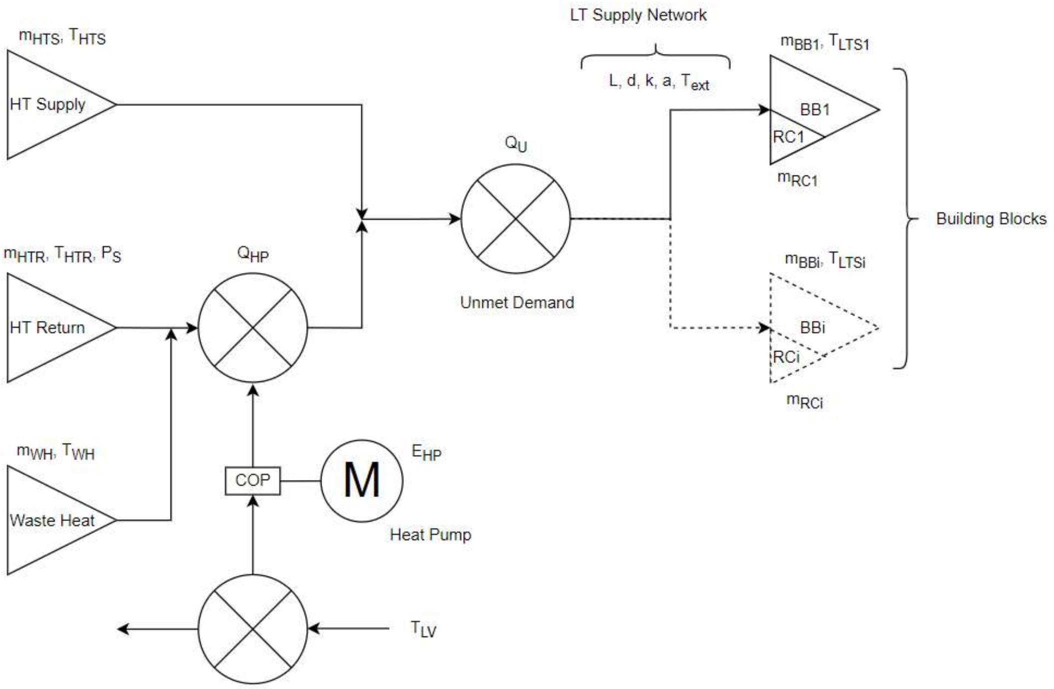

Figure 38: S3 LT Supply pandapipe model

The COP of the heat pump is calculated in a method adapted from Lund [48] and Arnaudo [13] shown below, where the COP is dependent on the logarithmic mean temperature difference at the evaporator T_{low} and condenser T_{high} as well as a Carnot efficiency η and a parameter β accounting for the temperature drop across the evaporator and condenser.

$$COP = \eta_{Car} \frac{T_{high}}{T_{high} - T_{low} + \beta} \qquad (8)$$

$$T_{high} \text{ or } T_{low} = \frac{T_{in} - T_{out}}{\ln\left(\frac{T_{in}}{T_{out}}\right)} \qquad (9)$$

Following the two stage ammonia heat pump developed in detail by Volkova in [17] for a similar application in Tallinn the COP will be modeled with η_{Car} = 0.555 and β = 2. The water temperatures were obtained from instruments in the existing Ropsten heat pump plant. A constant temperature drop of 3°C was used for the sea water moving through the heat pump, again mirroring the application in Tallinn.

When evaluating the performance of a proposed heat pump system it is normal to specify a maximum heat output. This is normally done in combination with an economic assessment, as the full HP output might be rarely used and costly to install. However as this work is intended to investigate the maximum that alternative supply scenarios could provide heat to a LTD no maximum electrical or heat power will be specified.

5.3.5 Scenario 4: Prosumers in the LTN

The prosumers in the network are modeled on a nominally sized Swedish grocery store with the chilling requirements shown in Figure 39. This comprises a year round freezing need of 35kW and a maximum refrigeration need of 200kW, 50% of which is required at 5°C [52].

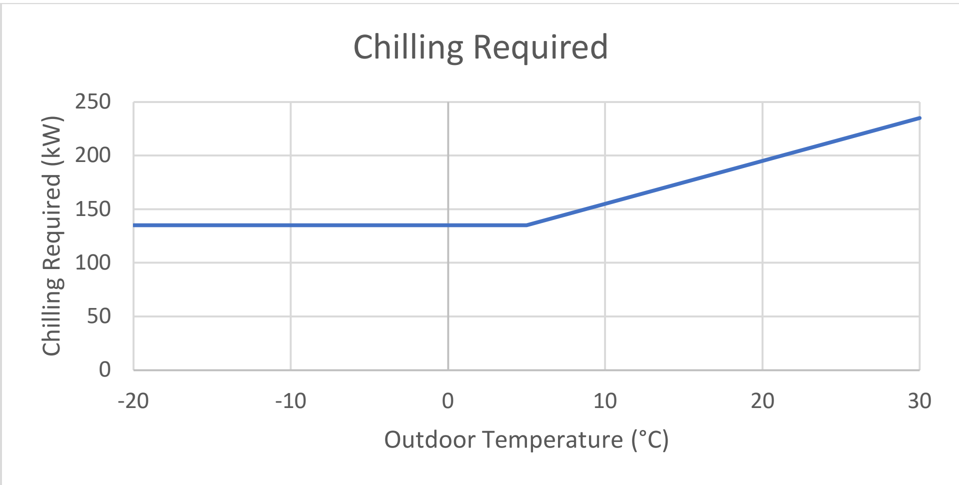

Figure 39: Chilling Required by Prosumers

Four prosumers are implemented in the district, representing for example two grocery stores, an ice rink chiller in the sports hall, and a large air conditioning unit in one of the commercial buildings. In total this represents a minimum chilling need of 540kW and a maximum of 940kW. Note this amount is only the rejected heat and does not include the energy from electricity rejected as part of the heat pump operation.

As trans-critical CO_2 chillers to not have a constant condenser temperature (as the condenser is operating above the critical point of the refrigerant) the Lorenz efficiency must be used rather than the Carnot. The condenser temperature is taken as the mean condenser temperature and the evaporator temperature is fixed. In a grocery chiller application the lower temperature T_{low} is fixed -10°C, allowing it to both maintain a refrigeration temperature of -3°C and accept heat from the low temperature chiller maintaining the freezer temperature at -18°C.

The condenser temperatures are determined by two factors. To avoid frosting on the ambient cooling coil in the case of below zero ambient temperatures there is typically a minimum condenser temperature, below which the refrigerant temperature will not drop regardless of the ambient temperature. When rejecting heat to the ambient this temperature is driven by ambient humidity conditions, a range of minimum temperatures has been discussed, but a central value proposed by Sawalha is 10°C [52]. The condenser inlet temperature is determined by the design of the chiller and the characteristics of the refrigerant, but can also be controlled by varying the compressor pressure to achieve a target temperature. This is useful for discharging to varying ambient conditions or to meet a temperature setpoint for district heat deliveries.

$$COP = \eta_{Lor} \frac{T_m}{T_m - T_{low} + \beta} \tag{10}$$

$$T_m = \frac{T_{in} - T_{out}}{2} \tag{11}$$

In developing a method to screen potential heat sources against one another, Reinhold advises using η_{Lor} of 50-60% for trans-critical CO_2 chiller applications [74] (this work will use η_{Lor} = 55%), and Sawalha a β of 5°C for supermarket applications.

The electricity use under normal conditions of the chiller operating in FPC mode and rejecting heat to the ambient represents a baseline of electricity usage to perform the cooling service throughout the year. As some electricity would therefore be used by the grocery store chiller whether or not acting as a DHN prosumer, only the additional electricity required to deliver heat to the higher temperatures of the DHN should be considered in determining the electrical intensity of the scenario. For this a COP_{HR} is defined as [49]:

$$COP_{HR} = \frac{Q_{del}}{E_{Pro} - E_{FPC}} \tag{12}$$

Where Q_{del} is the heat delivered to the DHN, E_{Pro} is the electricity consumed by the prosumer's chiller, and E_{FPC} is the electricity that would be consumed operating the same chiller with floating point condenser mode.

As CO_2 refrigerant exhibits significant non-linear enthalpy changes around the critical point it is necessary to calculate the fraction delivered to the DHN as opposed to the ambient conditions using the enthalpy of the refrigerant.

In S4a prosumers deliver to the LT supply line and have priority in the district's merit order, with the remaining heat demand made up as described in S1 from HT Supply and Return. In S4b as prosumers deliver to the LT return line, the districts heat demands are supplied exactly as in S1, as there is no opportunity for the prosumer heat to supply the LTD's demands.

5.3.6 3rd Pipe Scenarios

Each of the Scenarios 0, 1, 2, and 3 has a 3rd Pipe option on the return side of the network. As discussed in Section 2.2.4: Parallel Substation, the temperature of the return flow in the network can be elevated when there is low space heating demand or when recirculation is required in the network to maintain operating parameters. This 3rd pipe allows hot water from either of these sources to be separated from any colder return water, for example from DHW loss reheating, and thereby produces a "warm" and "cold" return. A separate 3rd Pipe return network, seen in Figure 40, is also created alongside the LT Return network to analyse the temperature and pressure profile in the 3rd Pipe.

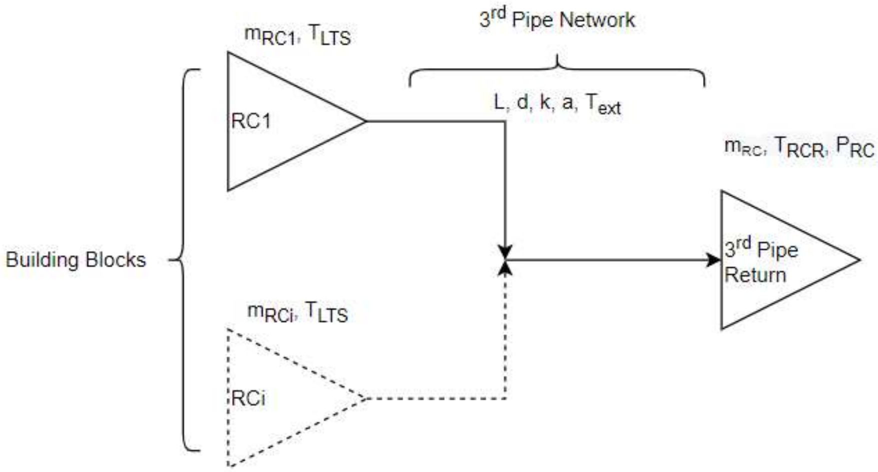

Figure 40: Scenario 3 3rd pipe pandapipes model

The recirculation flow $\dot{m}_{RCi}$ always flows directly to the 3rd Pipe network, however the return temperature T_{LTRi} of the BB substation $\dot{m}_{BBi}$ determines which network the substation return will flow to. As seen in Figure 41, if the return temperature of the BB is above 40°C the flow will divert to the 3rd pipe network to avoid warming the return network. This temperature limit may be reached for example when there is no SH or DHW demand, and the only remaining demand is making up the heat losses of circulating the DHW.

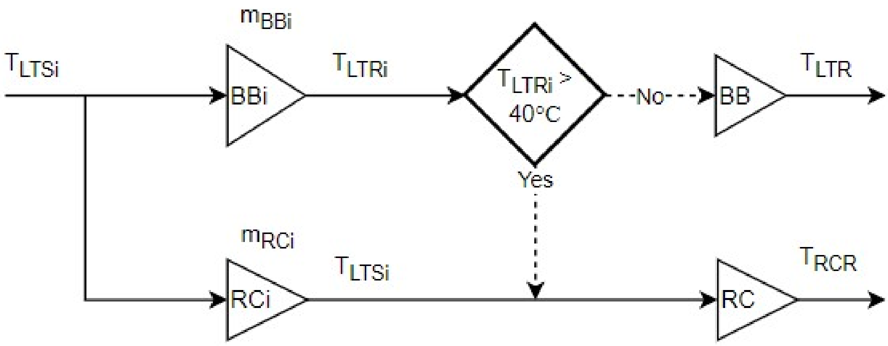

Figure 41: Flow control within the BB substation

In scenarios that do not have a 3rd pipe, any recirculation flow is directed into the return network.

6 Results

The results of modeling the heat demand and network of the case study district are presented first. Then, to gain a better overview of the results within and between scenarios, an overview of each scenario will be shown followed by several metrics that compare scenarios.

6.1 Low Temperature District

6.1.1 LTD Heating Demands

The heating demands of the buildings in the Loudden district are displayed together below in Figure 42, at hourly resolution from the year 2020. They include SH and DHW. The heat demands were produced by PlanHeat and adjusted to the specifics of the case study as described in Section 3.2: Heat Demands. The DHW demands were adjusted based on the seasonal incoming water temperature, and the SH demands adjusted to meet the targeted specific heat consumption for buildings in NDS.

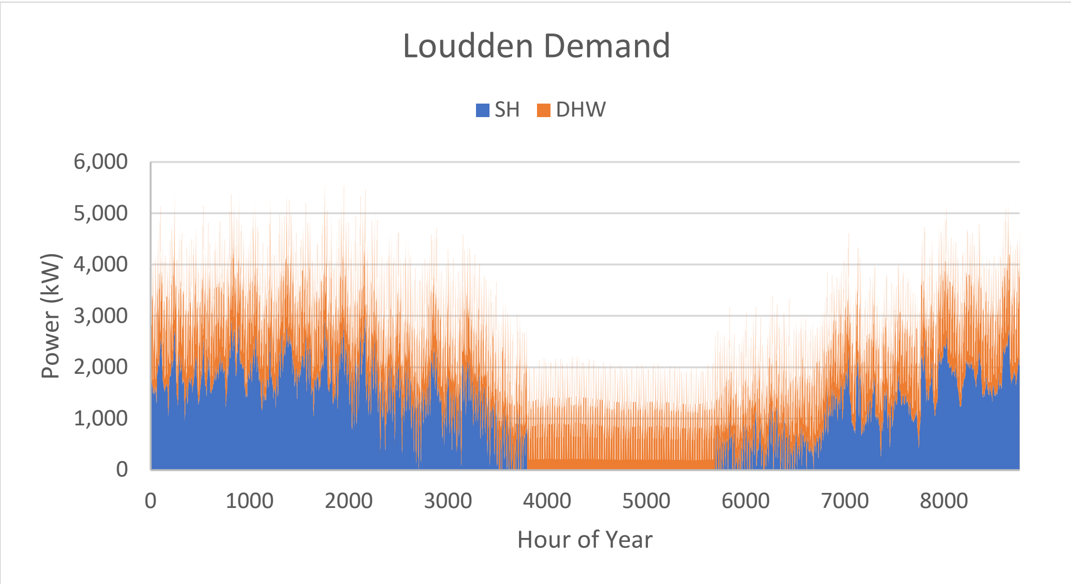

Figure 42: Total Hourly Heating Demand for Loudden District

For the year 2020 the Loudden district would be expected to require nearly 19 GWh of heat, supplied at a maximum rate of 5.62 MW. As expected for a LTD, SH forms a smaller share of the total heat demand than in older districts. In Loudden this effect is exaggerated slightly due to the high DHW demands of the sporting facility included in the layout, which increases the DHW share of heat demand to 49%.

Table 4: Characteristics of Loudden Heat Demand

	Space Heating	Domestic Hot Water	Total
Annual Demand (MWh)	9,538	9,285	18,823
Peak Demand (MW)[15]	2.98	2.69	5.62
Minimum Demand (MW)	0.00	0.26	0.26

Seen in Figure 43, Residential SH and DHW demand form 85.7% of heat demand, with the Sport facility DHW production (8.9%) and Commercial SH (4.8%) making up much of the remainder.

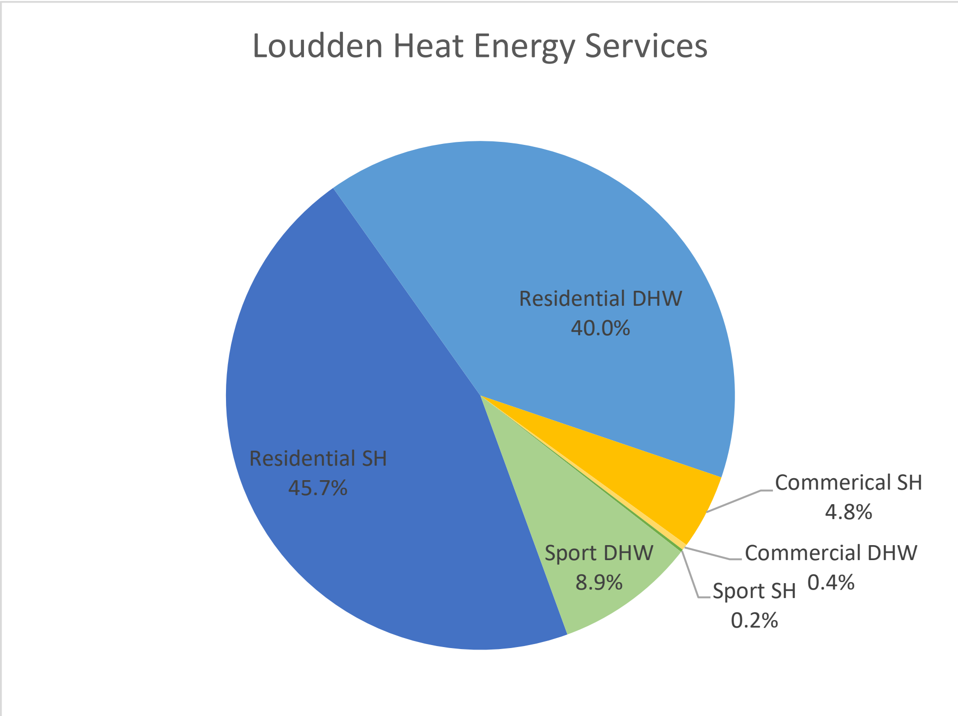

Figure 43: Annual Loudden heat energy demands among the building and service types

The three building uses show significantly different specific heat demands, as seen below in Table 5. The commercial premises use significantly less DHW per square meter than the residential buildings, however as 93% of the commercial space in the district is of older construction it requires higher specific SH. In sport facilities' (here modeled as a single building) heat demand is dominated by the DHW. The specific SH demand is significantly

[15] The Total Peak Demand is not the sum of the peak SH and DHW demand as these peaks occur at different times.

lower than residential properties, as the users and equipment of sports facilities contribute significant free heat to the building.

Table 5: Specific Heat Demands of Loudden Buildings

	Residential	Commercial	Sport
SH Demand ($kWh/m^2/y$)	16.2	42.1	5.2
DHW Demand ($kWh/m^2/y$)	14.2	3.3	261.8
Total Demand ($kWh/m^2/y$)	30.5	45.4	267.0

While the SH demands follow the outdoor temperature, shown in Figure 44 for the first week of the year, the DHW demands show a distinct daily and weekly cycle seen in Figure 45 below for a one week period (Sunday-Saturday). The peak morning and evening demands are driven by residential consumers, who also create a small DHW demand through the night. Commercial buildings demand only a very small amount of DHW during weekdays while the sporting facility produces the remainder of the demand. The nominal peak DHW demand is of constant magnitude throughout the year, but is adjusted in this work based on the incoming potable water temperature as discussed in Section 2.2.2: Domestic Hot Water.

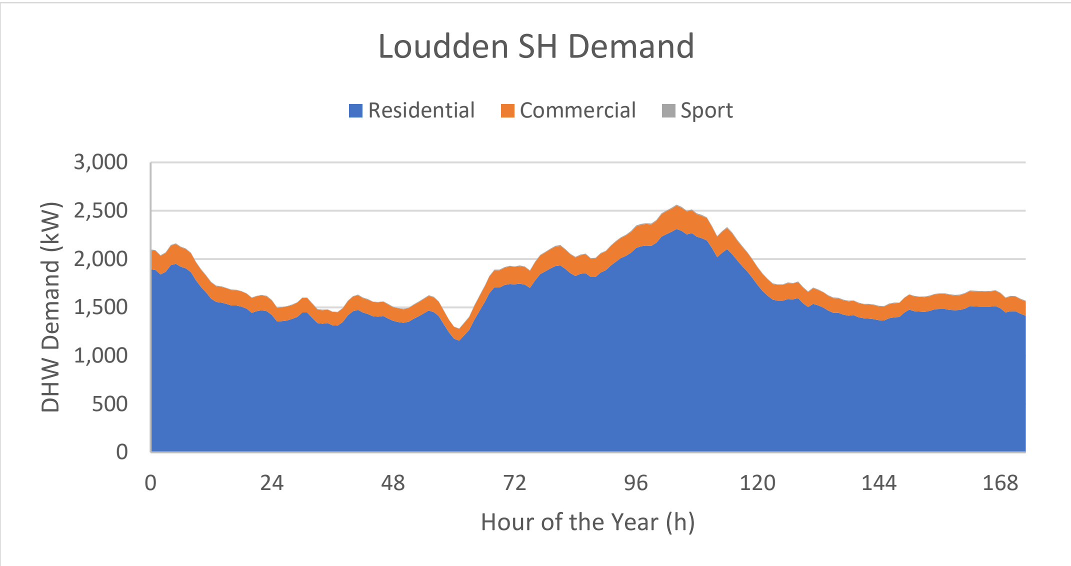

Figure 44: Loudden SH Demand for the 1st week of the year

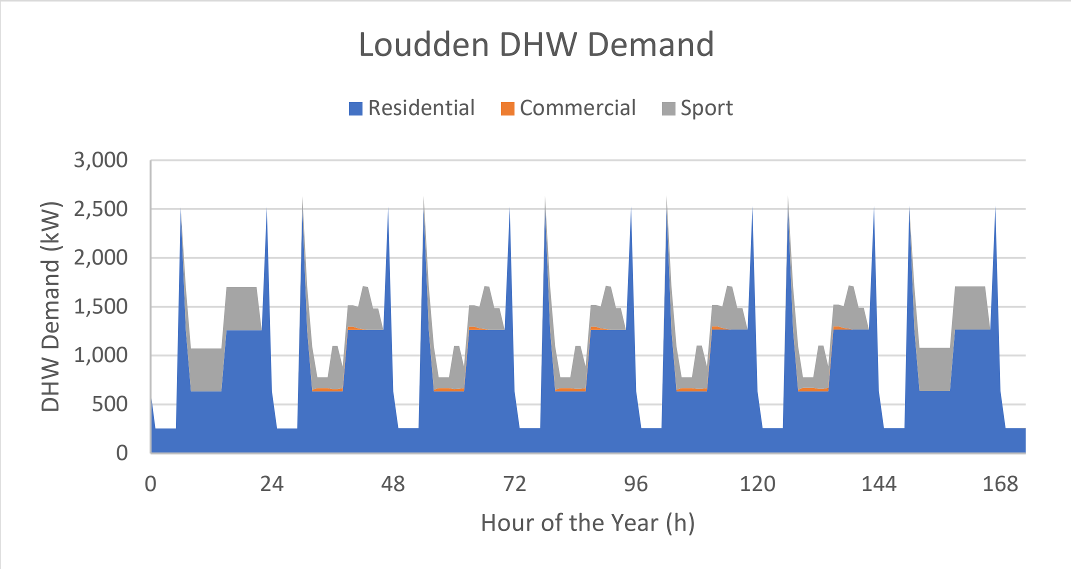

Figure 45: Loudden DHW Demand for the 1st week of the year

6.1.2 LTN Pipe Sizing

When comparing to an early stage overview of the network design from Stockholm Exergi[16], presuming conventional construction of buildings and the network, it can be seen in Figure 46 that the high efficiency construction combined with the use of plastic piping allowed for smaller pipes. This is due in part to the lower pressure drops enabled by the plastic piping as well as the reasonably high delta T seen in the LTD due to the 3-Stage substation design.

[16] This conventional design was not dimensioned as part of this work and is used as a reference case only.

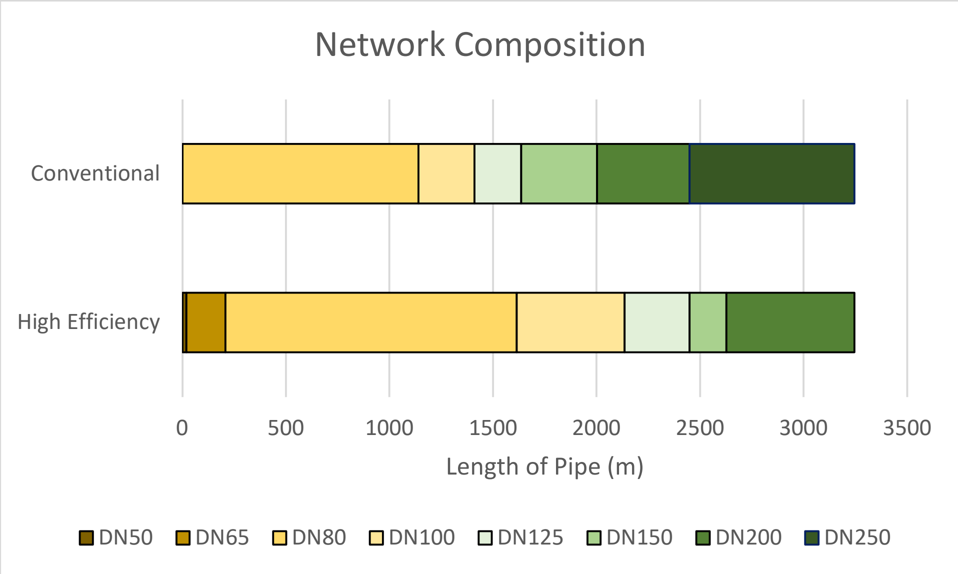

Figure 46: DHN Pipe Size Composition with Conventional and High Efficiency Buildings

6.1.3 Linear Heat Density

The Loudden LTN comprises of 3.25 km of piping in each of the supply and return networks. With an annual demand of 18,800 MWh this amounts to a linear heat density of 5.9 MWh/m/yr. This falls squarely within the 4.2-6.9 MWh/m/yr stated by Werner as typical linear heat densities in built up areas [75].

6.2 Scenario Results

6.2.1 Description of Heat Recovery Bands

To extend the discussion beyond the net heat energy requirement seen frequently in LTDH literature, the energy requirement has been separated into different temperature levels that are available to a DHN operator. This technique, not seen before in similar works, allows a DHN operator to evaluate how these opportunities would fit within their operation.

A description of the heat bands is shown in Figure 47. This diagram is drawn from S1a, but can be extended to the other scenarios. The diagram places the LTD within the wider DHN and shows the interactions between the two. Several effects of adding a LTD to an existing DHN can be seen.

- First is that the flow utilised in the LTD $\dot{m}_{LTD}$ returns to the main network at a lower temperature T_{LTR} than the existing HTN return flow T_{HTR}.
- Second, some amount of new HTN supply flow $\dot{m}_{HTS}$ is required that adds to the total mass flow of the network.

- Third, the heating required to supply the demanded energy to the LTD can be broken into three segments. These segments are
  - Heating the entire flow from the LTD $\dot{m}_{LTD}$ from T_{LTR} to T_{HTR}, in blue. This is heat recovery that would not be possible without the lower return temperature of the LTD
  - Heating the new HTN supply flow to the LTD $\dot{m}_{HTS}$ from T_{HTR} to the highest available waste heat temperature T_{HWH}, in orange. This is waste heat recovery that is already possible with temperature levels in the HTN.
  - Heating the HTN supply flow to the LTD $\dot{m}_{HTS}$ from T_{HWH} to T_{HTS}, in red. This is new high temperature heating that was not required before the addition of the LTD.
  - Note that the HTN return flow $\dot{m}_{HTR}$ would already have been heated from T_{HTR} to T_{HWH} and from T_{HWH} to T_{HTS} without the LTD, as a part of the grey area in existing network operation.

This diagram can be generalised to several cases, for example if the LTD was supplied with only HTN supply flow. Additional diagrams illustrating 3rd Pipe flow, additional waste heat flows, and the impact of prosumers delivering to the LTS and LTR lines can be found in Appendix A: Heat Band Allocation Diagrams.

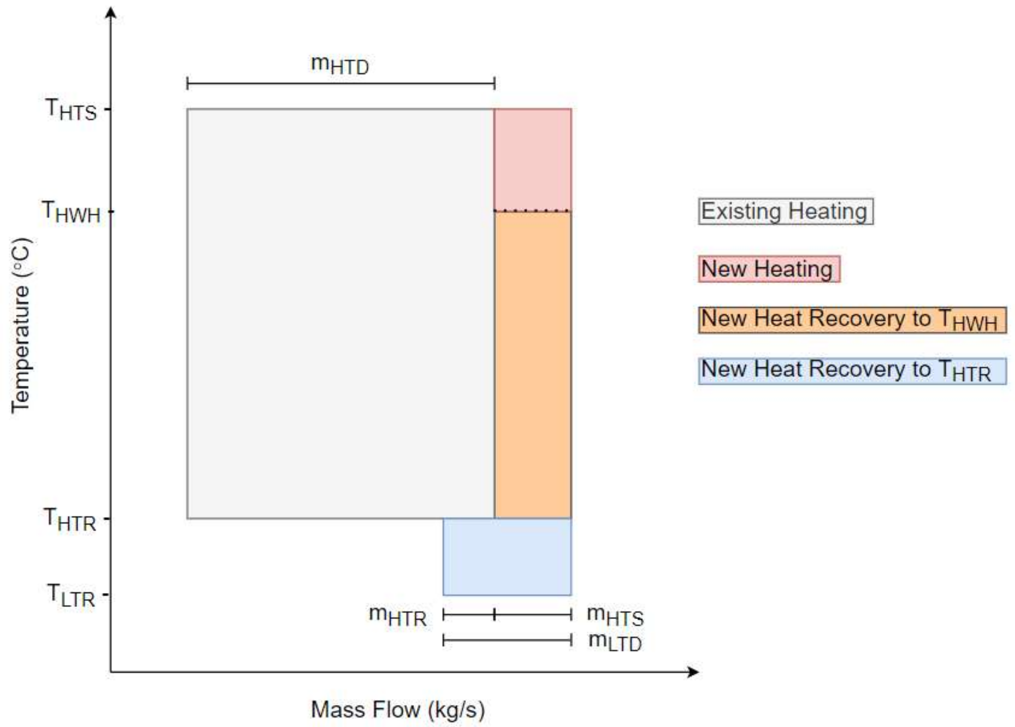

Figure 47: Depiction of Heat Recovery Bands utilised in this work, S1a

Two end cases of supplying heat to the LTD can be generalised for all of the scenarios in this work, in particular applied to heat recovery and emissions generation. The first is that no heat recovery is attempted in either the blue or orange sections of Figure 47. This corresponds to requiring new high temperature heating capacity to make up all of the energy required for the LTD. At the other end of the spectrum is a case of maximum heat recovery where the blue and orange areas are heated entirely with ambient heat, waste heat, or other heat recovery operations with no emissions impacts. This leaves only the red area as needing to be met by new high temperature supply, if the flow was to be returned to the HTN. In the ideal case for a LTD the T_{HWH} would be above the LT supply temperature and there would be no need for high temperature heat supply.

6.2.2 S0 Results

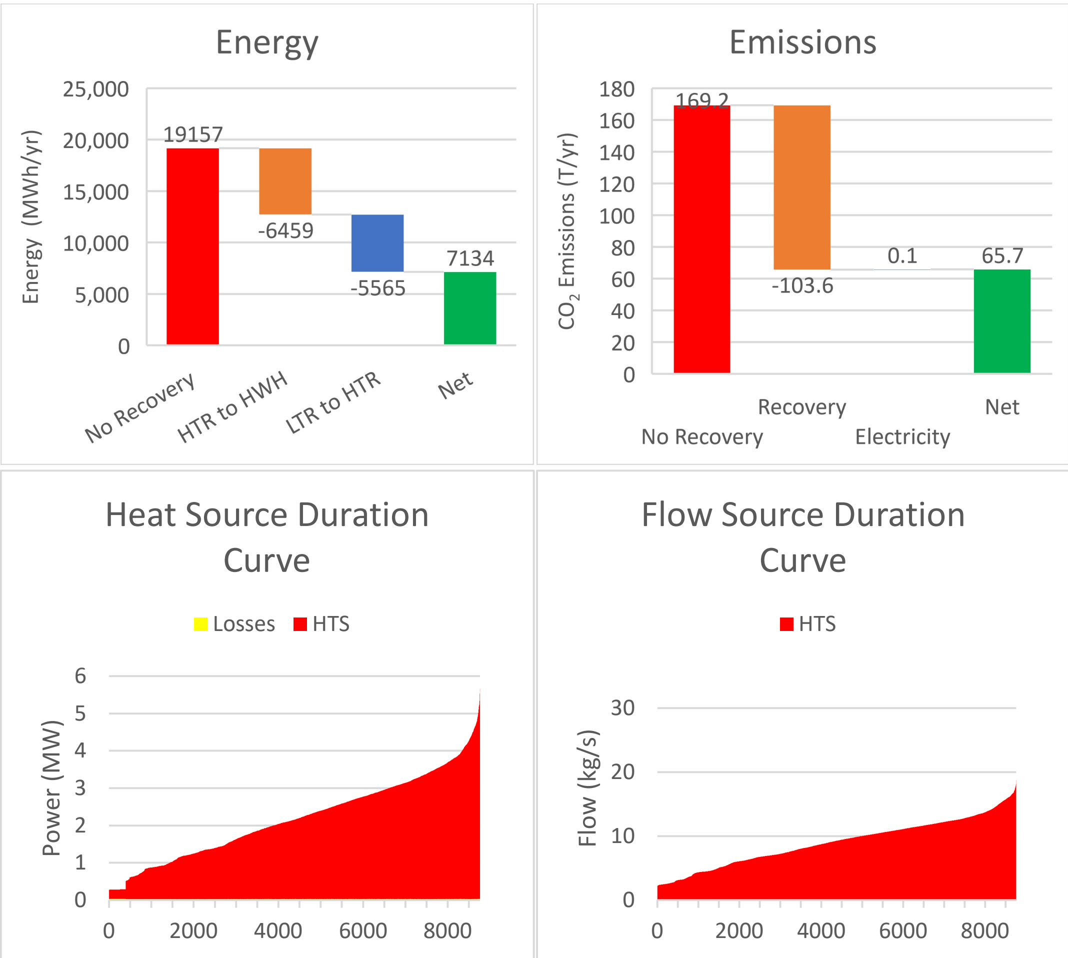

Figure 48[17]: S0a Results - Heat Recovery Bands, Emissions Production, Heat Source Duration Curve, and Flow Source Duration Curve[18]

[17] In this section the four-part figures will be named “a” through “d” in the order left to right, top to bottom.

[18] The vertical scale of Figure 48d has been increased to match the scale seen in later scenarios for better comparison.

A brief description of the results layout will follow here, and can be applied to the other scenarios as well. Within Figure 48a the first, red, column the heat energy requirement can be seen if no heat recovery is attempted and the entire return flow from the LTD is heated from T_{LTR} to T_{HTS} in a heat plant. Next to the right, in orange, the amount of heat that could be recovered with return flow between the temperatures T_{HTR} and T_{HWH}. This would be the temperature range that many conventional flue gas condensers and direct waste heat recovery systems would operate within. One step further right, in blue, is the amount of heat that could be recovered with the flow between T_{LTR} and T_{HTR}. This is new heat recovery that the low return temperatures of LTD make available. Finally, furthest right, in green, lies the remaining heat that is required between T_{HWH} and T_{HTS}. This amount represents the high temperature heat that is required to provide the HTN's supply flow. A similar methodology is followed for Figure 48b, with the emissions if no heat recovery is performed in red on the left, followed by the emissions avoided if all of the new and existing heat recovery possibilities are utilised in orange, then the emissions generated from the grid electricity utilised in the scenario in blue. This results in the net emissions of the scenario in green.

In S0: High Temperature Supply significant heat recovery possibilities in the temperature range T_{LTR} to T_{HTR} are created by the LTD. Amounting to 29.9% of the LTD's consumption the new low temperature heat recovery, in addition to the 33.7% of existing heat recovery possibilities available in the range T_{HTR} to T_{HWH} reduce the high temperature heat requirement to 37.2% of the LTD's consumption. This corresponds to an emissions reduction of 61.2% compared to supplying the LTD entirely with new high temperature heat[19].

It is noted that the emissions from the use of electricity is very minor in this scenario, accounting for 0.2% of net emissions.

[19] The emissions and heat requirements are not reduced by the precisely same amount as the average emissions from heating change throughout the year, as seen in Figure 20. Thus if high temperature heat requirements are reduced more in the winter during a period of higher average emissions, as is the case here, the emissions will reduce more than the heat requirements.

6.2.3 S1 Results

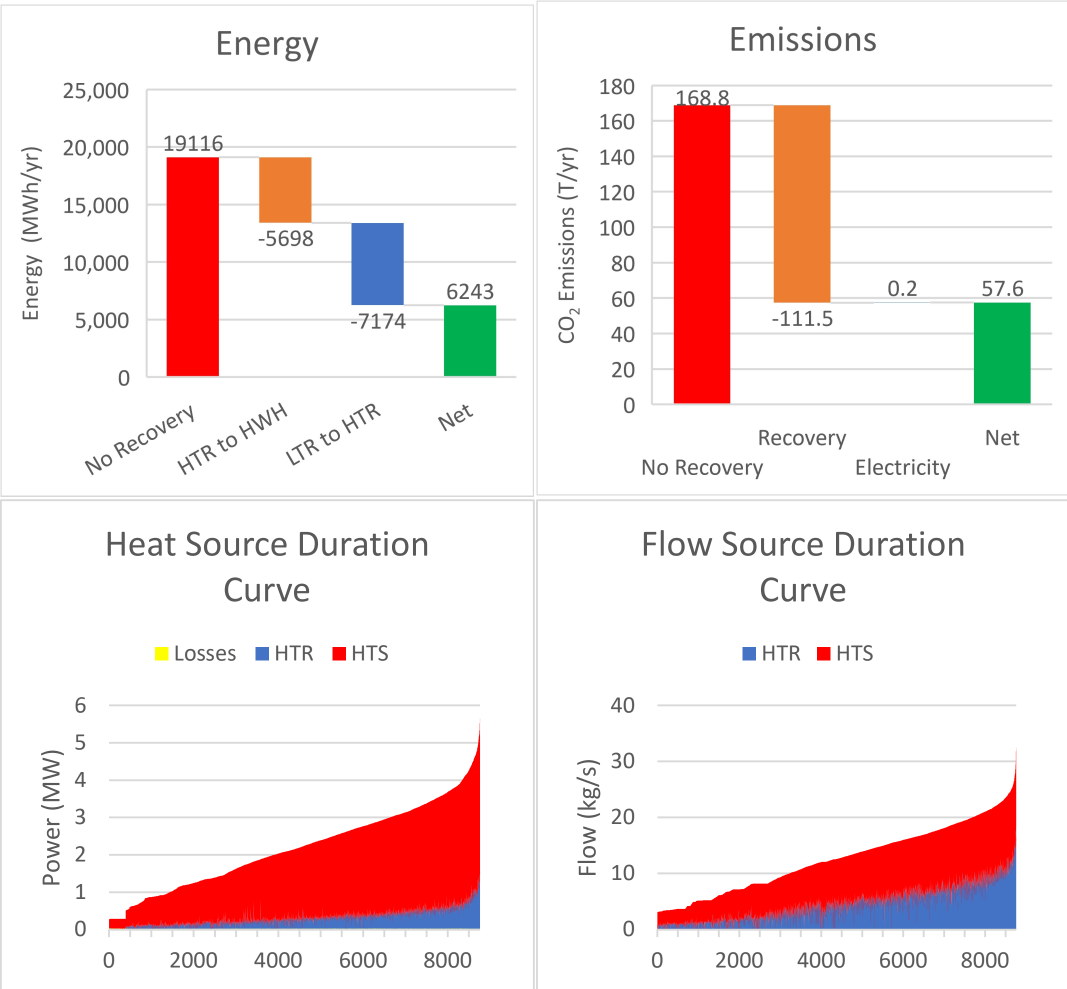

Figure 49: S1a Results - Heat Recovery Bands, Emissions Production, Heat Source Duration Curve, and Flow Source Duration Curve

In S1: Utilising HT Return Flow 28.9% more heat recovery is available in the T_{LTR} to T_{HTR} range and 11.8% less in the range T_{HTR} to T_{HWH}. The net effect of this is a 12.5% reduction in the amount of high temperature heat needed to supply the LTD. These changes are all due to the use of HT return flow. An increase in flow rate needed to supply the district (seen in Figure 49d), due to the due to the lower temperature difference between the districts supply and return temperatures, increases the flow returning at T_{LTR}. The use of HT return flow also reduces the amount of HT supply flow required, thereby reducing heat recovery possibilities in the range T_{HTR} to T_{HWH} relative to S0.

Of note is that while the HT return flow contributes 37% of the flow over the year, it contributes just 14% of the energy. This is due to the fact that the HT supply flow can supply a temperature difference of 58°C to the LTD compared to 15°C that the HT return flow can supply, on an annual mass weighted basis.

The electricity consumption in this scenario has increased by 2.1x due to the increased mass flow required. However, electricity still produces a negligible share of emissions at 0.3%.

6.2.4 S2 Results

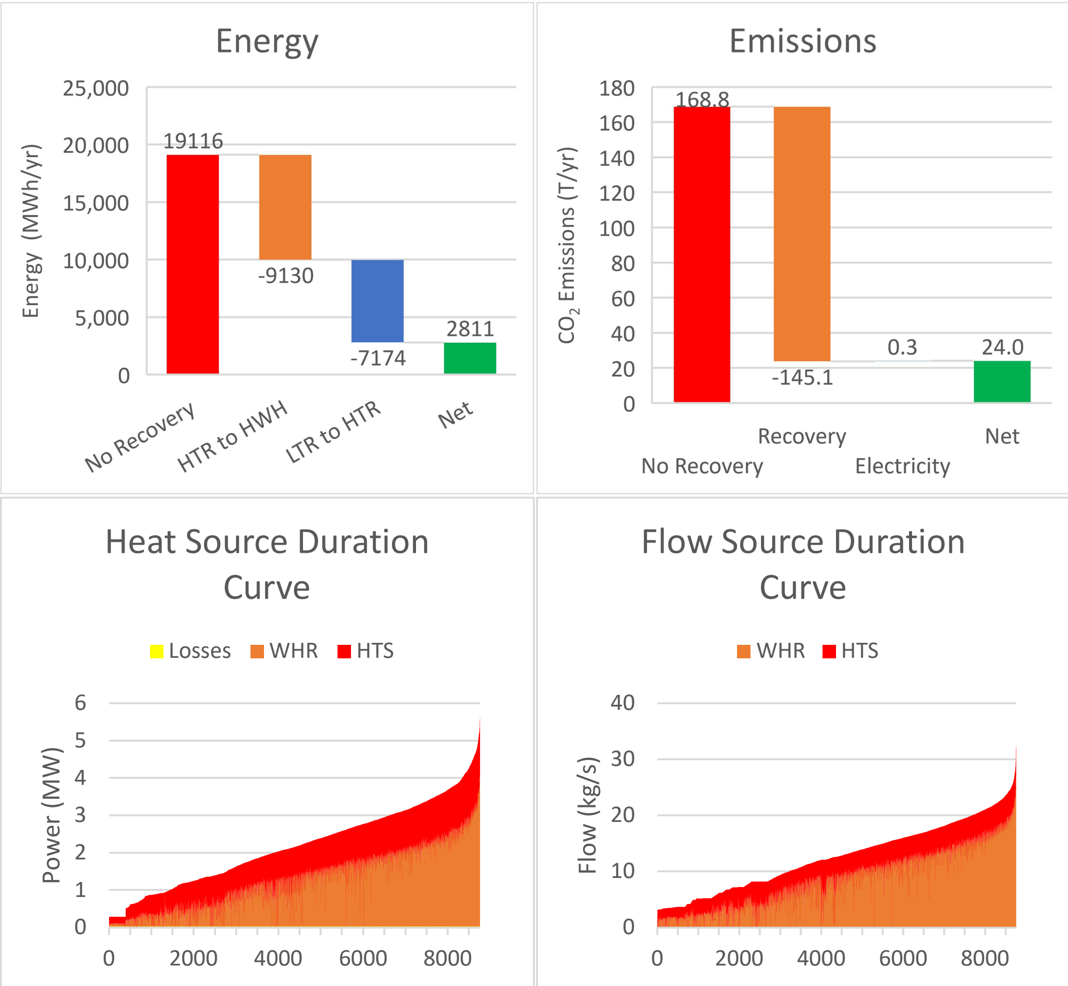

Figure 50: S2a Results - Heat Recovery Bands, Emissions Production, Heat Source Duration Curve, and Flow Source Duration Curve

When introducing a waste heat flow at 60°C in S2 alongside HT supply and return, it is seen in Figure 50 that the optimum selection is a mixture of the waste heat flow and HT supply flow. This is because throughout the year the waste heat flow has a higher temperature than the HT return flow, and thereby requires less HT supply flow to meet the LT supply target.

With the introduction of the waste heat flow we see a 60.2% increase in the possible heat recovery in the T_{HTR} to T_{HWH} temperature range relative to S1. No change is seen in the T_{LTR} to T_{HTR} temperature range, as the LT return mass flow remains the same in both scenarios.

The waste heat flow can supply up to 85% of the energy required to supply the LTD in this scenario. Similarly, emissions are reduced by 86% compared to heating the LTD with new high temperature supply.

6.2.5 S3 Results

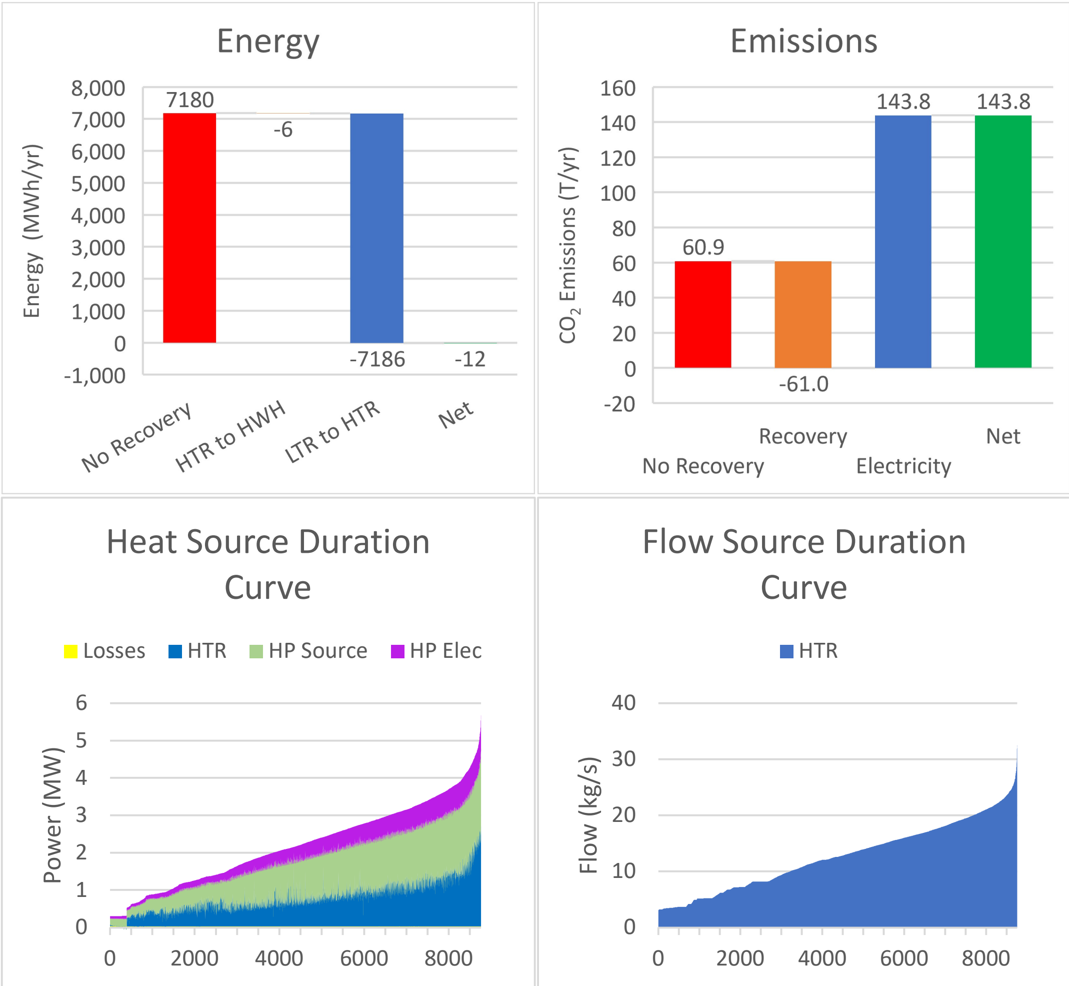

Figure 51: S3a Results - Heat Recovery Bands, Emissions Production, Heat Source Duration Curve, and Flow Source Duration Curve

In scenario S3: Utilising a Sea-Source Heat Pump it is noted that all of the heat energy required from the HTN can be recovered in the T_{LTR} to T_{HTR} temperature range[20]. This results in very close to zero net heat input from the HTN if heat recovery is utilised. The heat recovery can reduce the emissions from heat production from 61 T/yr to 0 T/yr, however the electricity consumed in the heat pump produces 144 T/yr of emissions. This is an

[20] This is due to the use of only HT return to provide mass flow in the LTD. In the case a different combination of mass flows was utilised this may not be the case.

important result, as it shows that merely electrifying part of the LTD heat supply does not inherently reduce emissions.

As an interesting point, at the lowest demand hours the HT return acts entirely as a mass source and does not contribute any energy to the district. This is because the LT return temperature in these hours is very close to the HT return temperature, as the demand consists only of reheating DHW losses which produce a high return temperature in both systems.

The HP operates with a 1st/99th percentile range COP of 3.38-4.33, as seen in Figure 52. As the COP is dependent on the difference between the source and sink there is some seasonal fluctuation. While the temperature of the sea source does rise in the summer, the temperature of the HT return sink also rises. This leads to the highest consistent COPs being during the early fall when the sea is still somewhat warm but after the heating season has begun and the HT return temperature has dropped from its summer highs. Note that the HT return temperature is the condenser inlet temperature, and that the condenser outlet temperature remains at the LT supply temperature.

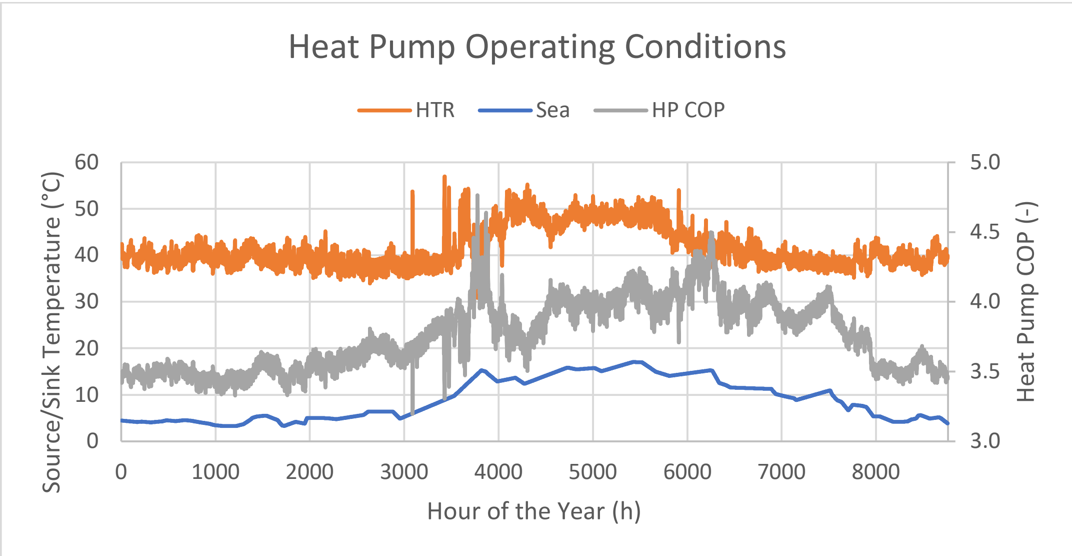

Figure 52: S3 Heat Pump Operating Conditions

6.2.6 S4a Results

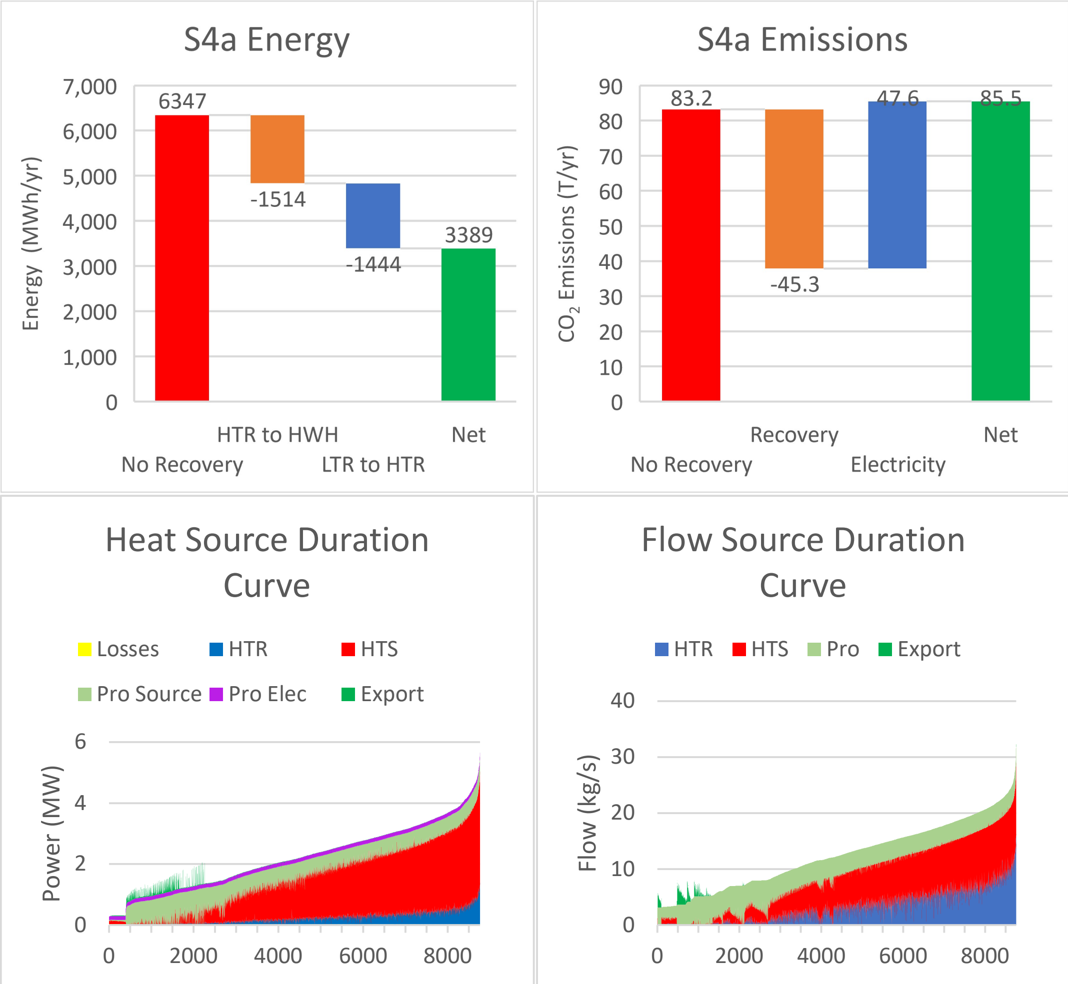

Figure 53: S4a Results - Heat Recovery Bands, Emissions Production, Heat Source Duration Curve, and Flow Source Duration Curve

The addition of prosumers in S4a: Prosumers to the LT Supply Line has several interesting effects. This first is that the total heat input to the LTD from the HTN drops by 66.8%. This is due to two reasons. First is that the prosumers supply 30.5% of the energy demands of the LTD, within the LTD. The second is that as the prosumers divert LT return flow from the LT return line into their heat recovery operations less LT return flow is sent to the HTN, thereby reducing the heating needs. This also has the effect of reducing heat recovery possibilities in the HTN significantly, by 73.4% in the range T_{LTR} to T_{HWH} and 79.9% in the range T_{HWH} to T_{HTS}, as much of this potential is used by the prosumers within the LTN.

The prosumers produce more heat at periods of lower demand, as these periods correspond to higher temperatures and hence an increased need for cooling in their operations. At periods of lowest demand however, when the return temperatures are highest, the prosumers are not able to deliver a large fraction of their waste heat into the LTN. The prosumers produce a surplus of heat in the district during the period when much of the network's supply is already from waste heat. The exported heat is therefore not as useful as if the prosumers were able to export heat at times of higher demand.

Higher prosumer heat deliveries to the LTN also correspond to higher flows through their operations, due to two effects. First, to deliver more heat at the same delivery temperature a higher mass flow is required. Second, in the periods when more chilling is required the LT return generally has a higher temperature, and so more mass flow is required to absorb the same amount of heat. During some periods in the lowest 2000 hours of demand the prosumers provide the entire needs of the LTD, and can even export a small amount. These exports amount to 0.7% of the LTD's annual consumption.

Producing the HTN energy required in this scenario with no heat recovery produces 50.7% less emissions than in the comparable non-prosumer scenario S1, and this amount of 83.2 T/year can be reduced by a further 54.4% to 37.9 T/year with the use of heat recovery. However, the additional electricity production required by the prosumers to deliver heat to the LTN produces 47.6 T/year. This produces a scenario that emits 48.4% more with prosumers than without (in the S1 case). This is notable considering the relatively high COP_{HR} that the prosumers deliver heat with.

As shown in other work and seen in Figure 54, heat recovery from chillers is possible at a high COP_{HR}[21] [49]. While there are both high and low anomalies the $5^{th}/95^{th}$ percentile COP_{HR} is 2.85-7.68 with an average heat delivery weighted COP_{HR} of 5.78. The COP_{HR} is declines quickly when the LT return temperature rises above 30˚C, an effect characteristic of trans-critical CO_2 chillers [52], and is highest when the outdoor temperature is highest. A high outdoor temperature reduces the additional electricity required to deliver heat into the LTN relative to the ambient, and thereby increases the COP_{HR}. As the LT return temperature nears 35˚C, and the temperature is dominated by reheating DHW losses, it is possible the prosumers would not deliver heat to the LTN in a market based control scheme.

[21] This is not to COP of the chiller itself, but the ratio of the heat delivered to the *additional* electricity required compared to discharging the heat to the ambient. The COP_{HR} can be particularly high in the summer when the LT return temperature is comparable to the ambient temperature and so little additional electricity is required.

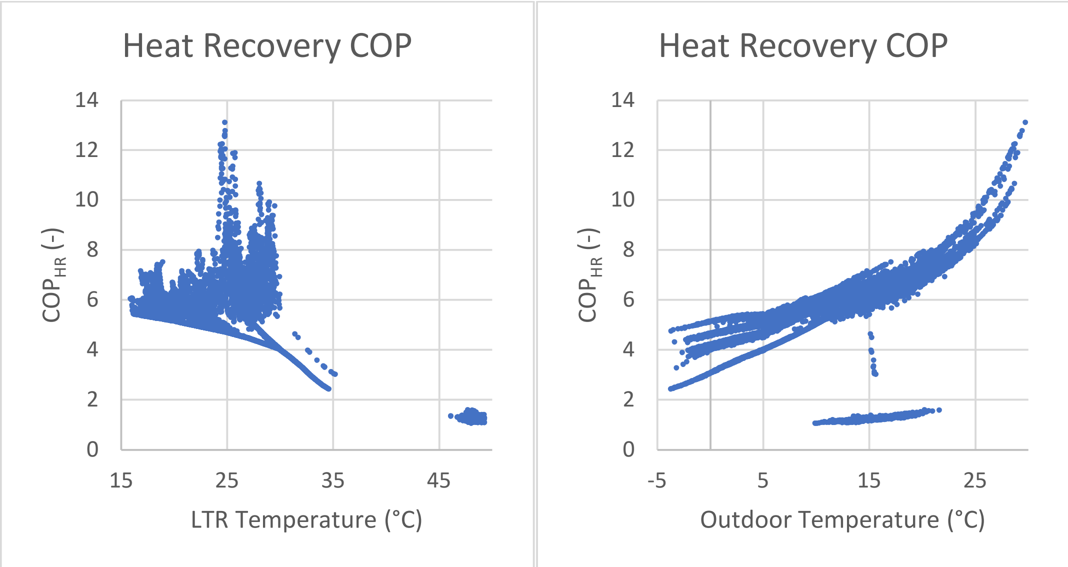

Figure 54: COP_{HR} in S4a: Prosumers to the LT return line

6.2.7 S4b Results

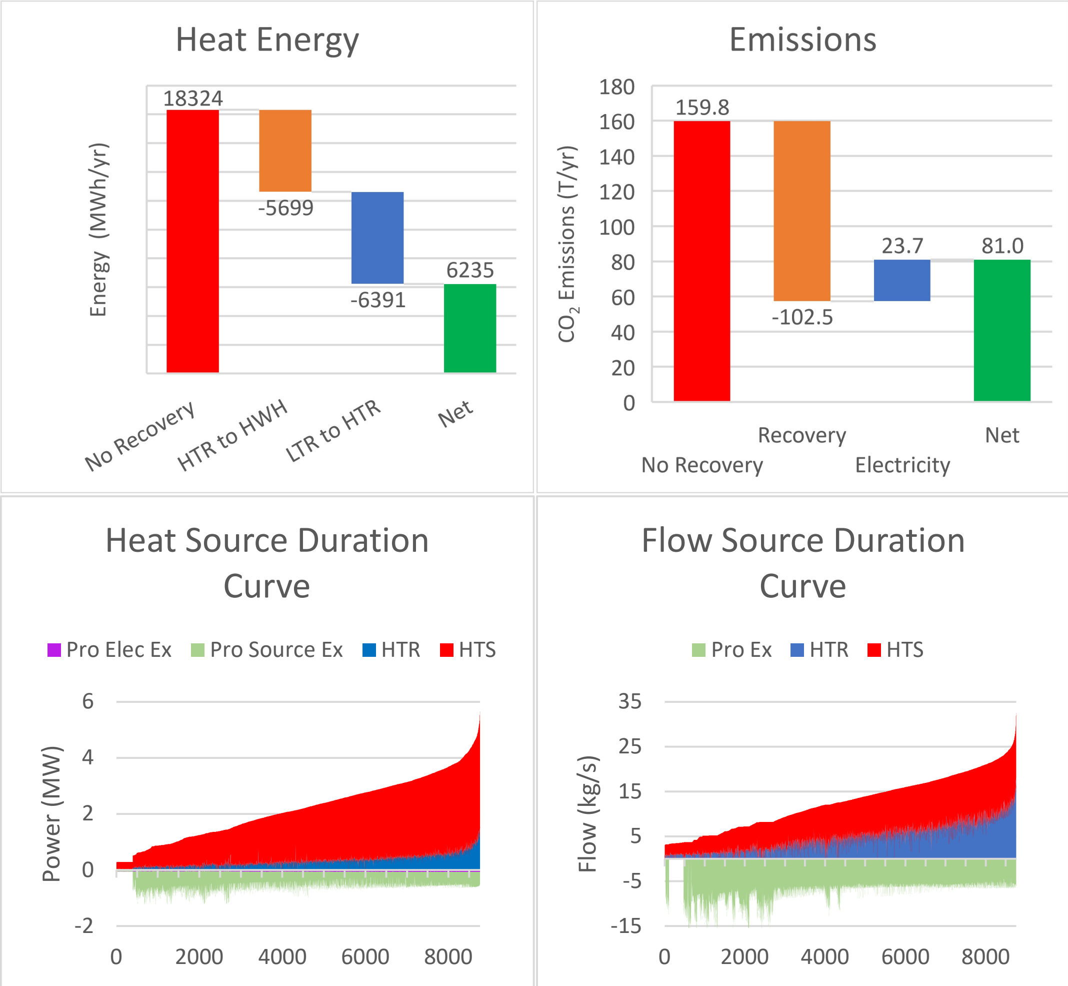

Figure 55: S4b Results - Heat Recovery Bands, Emissions Production, Heat Source Duration Curve, and Flow Source Duration Curve

S4b offers some interesting insights to the differences between arrangements of prosumers in the network. In this scenario prosumers deliver heat to the LT return line, and this means that all of the prosumer derived heat is exported from the network. This is unlike S4a where, as the prosumers deliver heat to the LT supply line, the district is able to self-utilise most of the prosumer's production. In this scenario an amount equivalent to 20.9% of the LTD's consumption is exported, with increasing exports in the low demand hours (due to higher outdoor temperatures) as the prosumers cooling needs increase.

The emissions from electricity are only 48.9% of those in S4a due to a higher COP_{HR}, however the higher heat demand to serve the district (as all the prosumer deliveries are exported) results in only 5.2% less emissions overall compared to S4a. Thus, despite the recovery of waste heat within the district the electricity consumption by prosumers to deliver to the LTN, even to the cooler return line, still results in 40.4% high emissions than the comparable baseline scenario of S1.

This scenario results in a substantially increased LT return temperature, seen in Figure 56. The LT return temperature is raised from a mass weighted average of 24.8°C to 32.0°C, an increase of 7.2°C. The LT return temperature is increased for all hours of the year, except for the 400 hours where the LT return temperature is higher than 45°C. It is important to note here that a higher return temperature in this scenario is not an indicator of poor temperature efficiency within the district, as it represents the utilisation of a heat recovery opportunity and does not increase the mass flow in the district. High return temperatures from, for example, a poorly performing substation result in higher network flows and lower heat recovery opportunities.

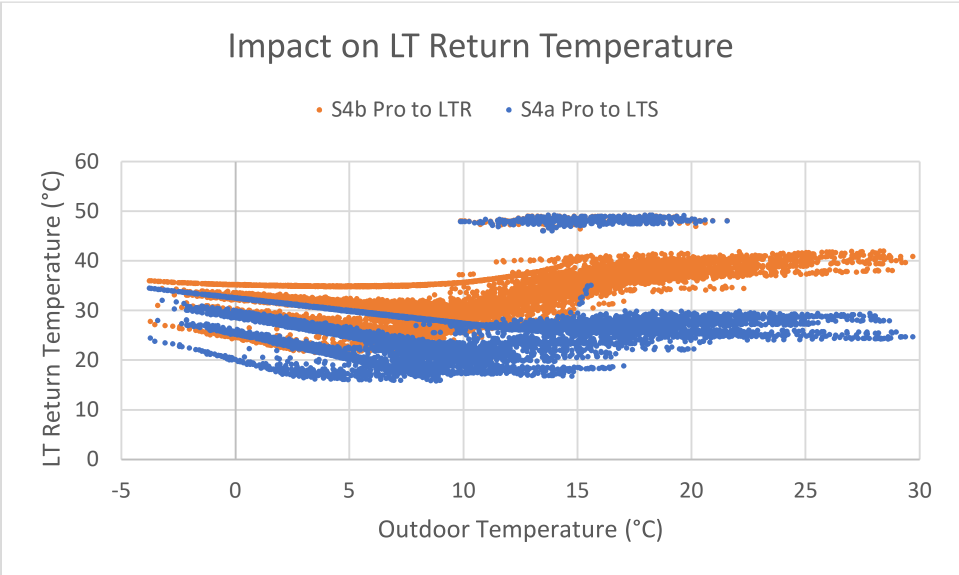

Figure 56: Impact of prosumers on the LT Return line temperature

In this scenario the prosumers COP_{HR} is very high, with a 5th/95th percentile range of 3.46-19.04 and a heat delivery weighted average of 12.26. In periods of high LT return temperature the prosumers do not produce (shown in Figure 57 as a COP_{HR} of 0), as their production temperature of 45°C is below the LT return temperature.

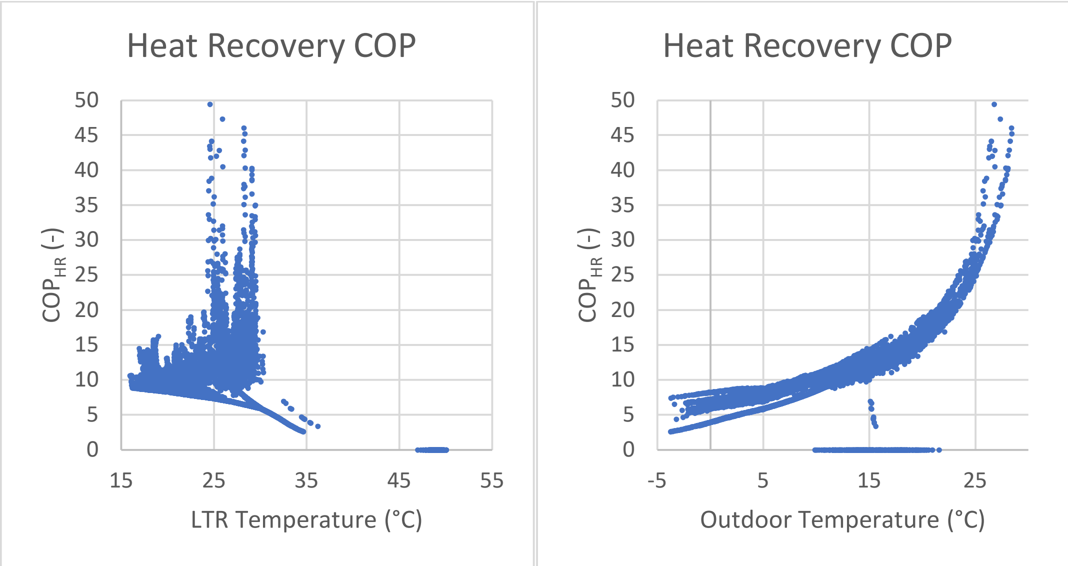

Figure 57: COP_{HR} in S4b: Prosumers to the LT return line

6.2.8 Effects of the 3^{rd} Pipe

Scenarios S0 S1, S2, and S3 were each modeled a) with and b) without a 3^{rd} Pipe. A common theme in the scenario results above is that the 3^{rd} pipe as operated made an, although measureable, insignificant difference to heat recovery opportunities and emissions production. This amounted to 7 MWh/yr for S0 and 5 MWh/yr for S1, S2, and S3 additional heat recovery possibilities. This is <0.05% of the 18.8 GWh/yr of heat demanded by the LTD, and a correspondingly small share in emissions reductions.

A 3^{rd} pipe operated only to divert high substation return temperatures above 40°C and a network allowable supply temperature rise of 5°C does not segregate very much flow with LTDH substation designs that are able to reduce the return temperature effectively, as seen in Figure 58. The 3^{rd} Pipe is used primarily at periods of low demand, when there is no SH or DHW demand and only the DHW losses are being serviced. Inconveniently this is precisely when the existing network has access to plentiful waste heat sources and so the benefits of a 3^{rd} Pipe, namely increased heat recovery and a source of mid grade heat, and not useful without long term thermal storage in the network.

It can also be seen that there is little to no flow division between the LT return line and the 3^{rd} pipe under these conditions; the return flow from the LTD is frequently either nearly all in the LT return line or the 3^{rd} Pipe. This also negates the use of a 3^{rd} pipe, as if the district normally produces very similar temperatures in similar hours[22], the return flow from the district will be the same whether it is coming from one pipe or the other.

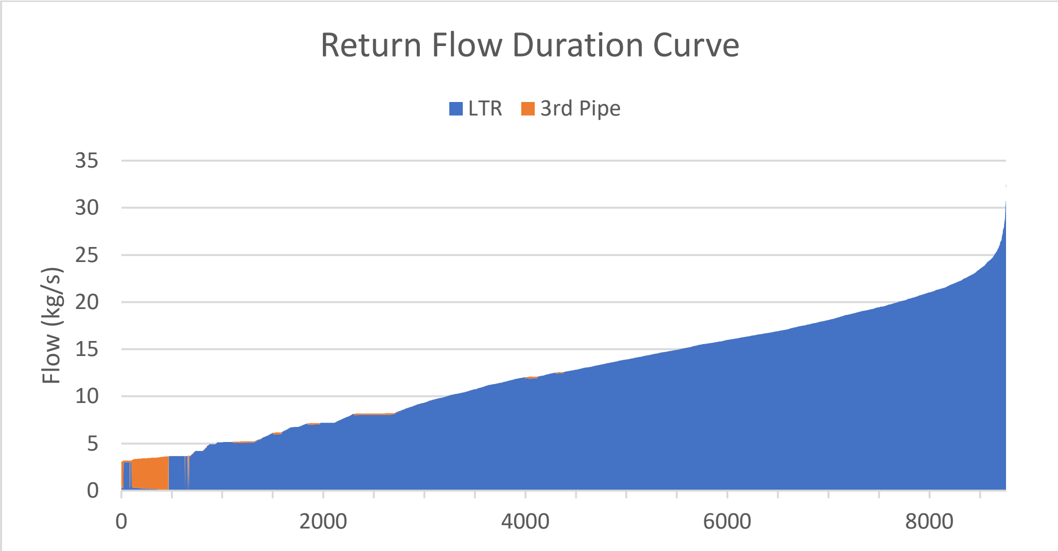

Figure 58: Return Flow Duration Curve for S1b

A 3rd pipe would be more useful in areas of different building use and age that would produce different return temperatures under similar conditions. The effect of DHW losses on 3rd pipe flow could be investigated, as reheating DHW losses without other demands causes high primary return temperatures. The primary flow required for reheating acts to maintain a minimum flow in the network and thereby reduces the need for substation bypass flow. Reducing the DHW losses beyond a certain, as yet unknown, point would require an increase in substation bypass flow to maintain supply temperature. However, larger DHW losses would also increase the flow of hot primary return and so the network return temperatures would benefit from a 3rd pipe. Several sensitivities around the 3rd pipe are investigated further in Section 7: Sensitivities.

6.3 Comparison Between Scenarios

6.3.1 Heat Supply Source

The most notable result is that while utilising the HT return and waste heat flows in S1 and S2 reduces the heat drawn from the HT supply line a significant fraction of energy is still supplied by new HT supply flow, 86% and 40% respectively. The addition of prosumers in S4a reduces the supply of HT supply and HT return proportionally to the prosumer production.

---

[22] Some of this effect could be a modeling artifact, as a real district may have more variation in DHW use through different hours of the day than is modeled here.

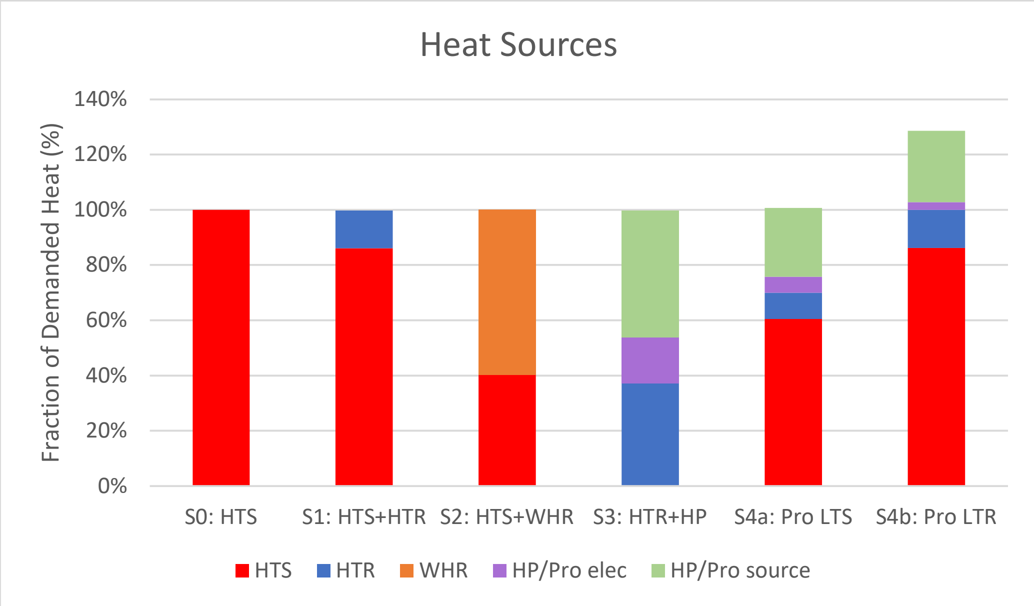

Figure 59: Heat Supply Sources for different scenarios

A major difference is seen here between S4a and S4b wherein prosumers deliver either to the LT supply or LT return line. When prosumers deliver to the LT supply line 97.8% of their production is consumed within the LTD. However, when prosumers deliver to the LT return line, there is no opportunity for the LTD to utilise the heat and it is entirely exported from the district.

It can also be seen that from S3 to S4a and S4b the use of electricity decreases. This will be explored further below in Section 6.3.4: Electrical Intensity.

6.3.2 Emissions Production

In Figure 60 the emissions of each scenario are shown for two end cases. The first case assumes no heat recovery with either new or existing opportunities and therefore all of the thermal energy required by the district is supplied by new generation according to the production mix discussed in Section 3.5: DHN Production and Emissions. This is shown in blue. The second case is that both the existing heat recovery possibilities as well as the new opportunities afforded by the LTD are utilised completely. This is shown in orange. Added to each of these are the emissions from electricity required by the scenario for pumping and heat pump operation in the LTD[23], shown in purple.

The scenario with the lowest annual emissions is S2: Utilising a Waste Heat Source when combined with heat recovery in the HTN. This is due to the high

[23] Note that some electricity is used in the production mix discussed in Section 3.5: DHN Production and Emissions, but this electricity is not shown separately in Figure 60 and would be included in the heat production emissions.

share of waste heat utilised in this scenario, and represents the application of the many levels of heat recovery available to a DHN operator to the supply of a LTD.

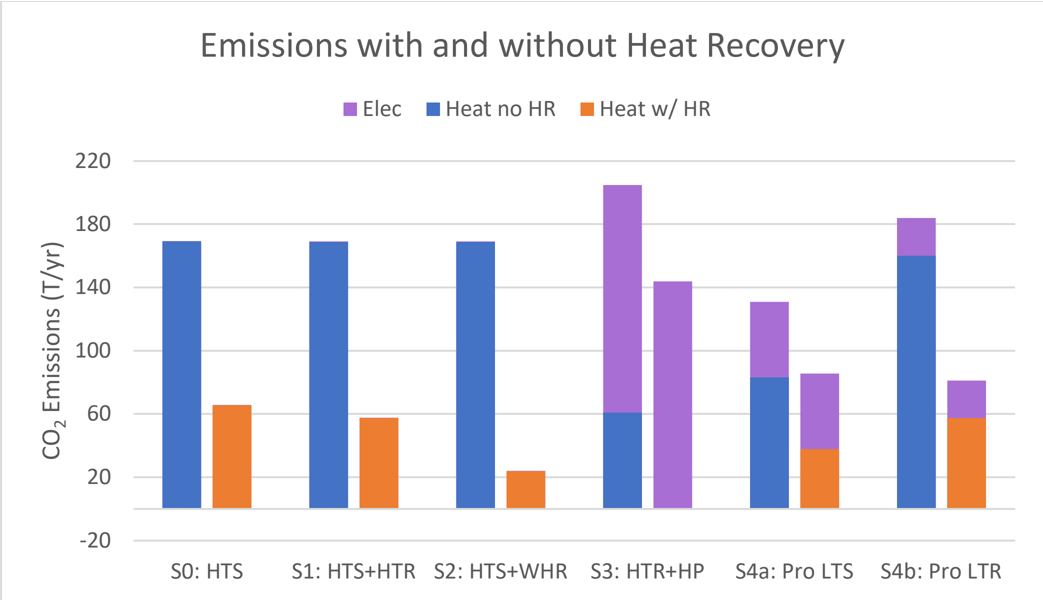

Figure 60: Emissions of scenarios with and without heat recovery

S3: Utilising a Sea-source heat pump produces the highest emissions both with and without heat recovery. This is a surprising result given the low average carbon emissions of Sweden's grid power; however this must be compared with the even lower marginal emissions from the SE production mix. It is also the case that prosumers using additional electricity to deliver heat to the LTN produces more emissions over the year than direct heat recovery within the existing network. This result indicates that the electrification of heating in a significantly decarboinised DHN should be pursued only with careful analysis.

6.3.3 Temperature of LT Return Line

The annual mass weighted return temperatures from the LTD are seen in Figure 61 for the four configurations that affect the return temperature: high temperature and low temperature supply[24], with and without the 3rd pipe return. The scenarios with the 3rd pipe result in a lower return temperature, with a reduction of 0.39°C for the HT supply and 0.34°C for the low temperature supply. As a comparison the annual mass weighted return temperature through the Gärdet HT Return line is 39.8°C, 14.9°C to 16.5°C higher than the LT return lines.

[24] High temperature supply corresponds to S0 and low temperature supply includes S1, S2, and S3.

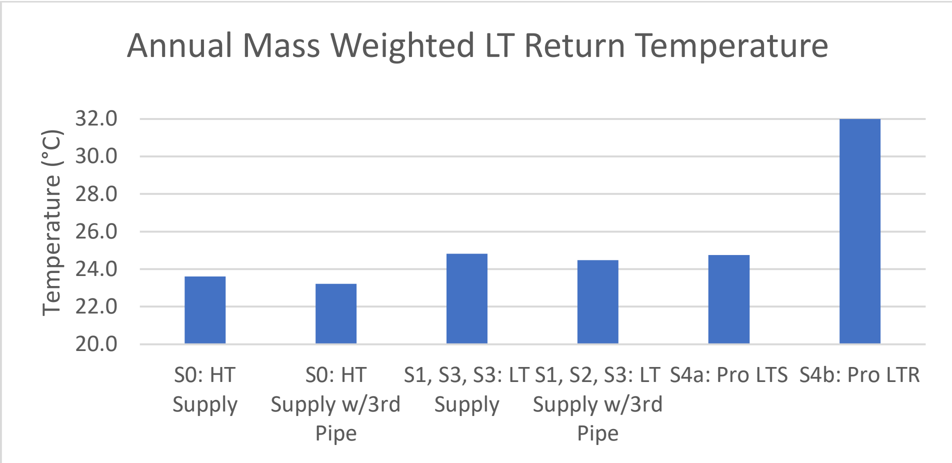

Figure 61: Annual Mass Weighted Return Line Temperature

Both the HT Supply scenarios return temperatures 1.2°C cooler than their respective LT Supply scenarios. This is due to the HT Supply flow requiring less mass flow to deliver the DHW loss energy and consequently causing less dilution of the remaining return flow with high temperature water.

S4a: Prosumer supply to the LT supply line results in a similar temperature to LT supply (0.1°C lower due to the slightly increased supply temperature from the prosumers), while S4b Prosumer supply to the LT Return line results in a significant increase of 7.5°C in LT return line temperature. However it is noted that the increase in return temperature in this scenario is not detrimental to network operation, as would be the case with a high substation return temperature. This is because the increased temperatures represent the utilisation of a heat recovery opportunity and do not increase the network flows.

6.3.4 Electrical Intensity of Heat Supply

The electrical use by the scenarios comprises of two components: the electricity required for pumping and the electricity required for heat pumps (if included in the scenario). In scenarios with a heat pump the electrical consumption is dominated by the HP.

Due to the increased mass flow required to deliver heat in the LT Supply scenarios compared to the HT Supply Scenario 2.1x more pumping energy is required over the year and the peak electrical demand rises by 3.8x, as seen in Figure 62. The 3rd Pipe increases the pumping demand only slightly, requiring 1.0% more electricity in both cases.

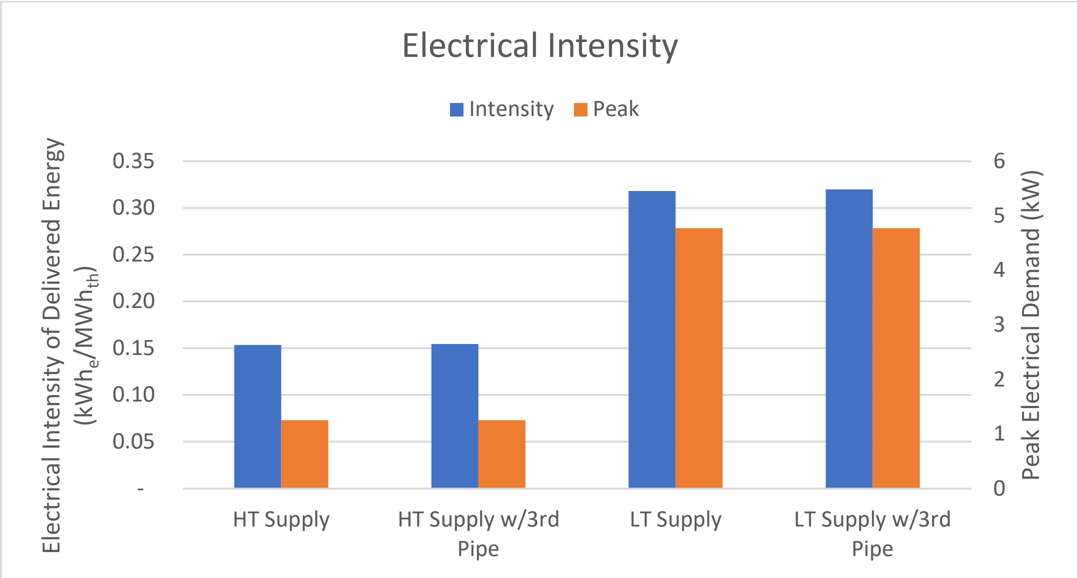

Figure 62: Electrical Intensity of Pumping in HT and LT scenarios

The electricity demand in S3 and S4 is significantly higher than in S0, S1, and S2 due to the electrification of part of the heat supply to the district, note the change of scale between Figure 62 and Figure 63. In Figure 63 it can be seen that the electrical intensity of S3 using a sea-source heat pump is much higher than the prosumer variations in S4. This is in part due to the higher COPs achieved by the prosumers, but also attesting to the fact that the sea-source heat pump provides a higher share of the total heat compared to the prosumer scenarios (62.7% as opposed to 30.5%).

It is noted that the energy produced by the prosumers in S4b is not consumed in the LTD but is exported.

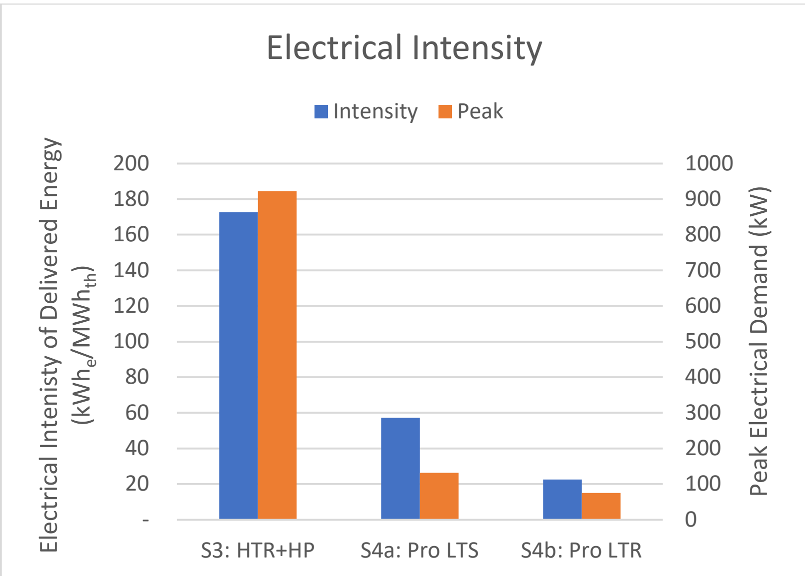

Figure 63: Electrical Intensity for S3 and S4

The peak electrical demand is proportionally lower compared to the electrical intensity in the prosumer scenarios, indicating that the peak electrical capacity is being utilised more evenly over the year. This effect can be seen more clearly in Figure 64 below showing utilisation of electrical peak capacity, or the annual MWh of heat energy delivered per kW of peak electrical capacity. Note the logarithmic scale. For the solutions that only use electricity to provide pumping energy the ratio is very high compared to those using heat pumps. However, even within the solutions utilising heat pumps there is significant differentiation relating to both the COP and the fraction of heat supplied by the heat pumps within those scenarios.

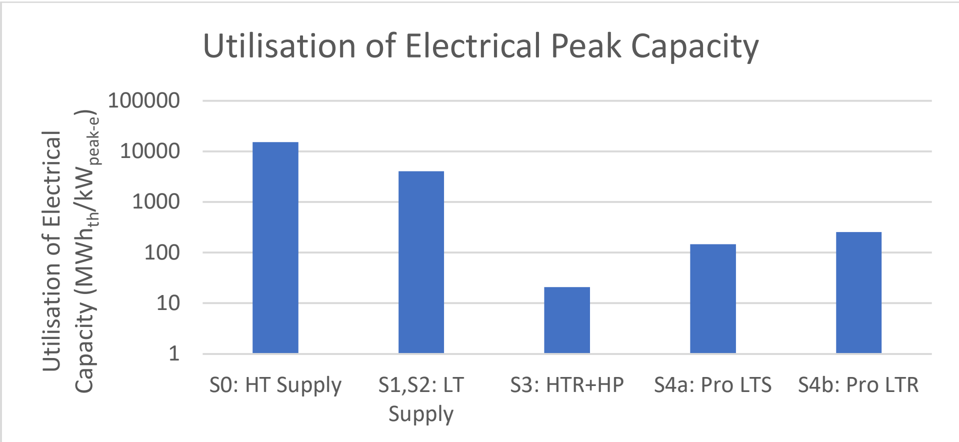

Figure 64: Utilisation of Electrical Peak Capacity, MWh thermal delivered per kW electrical peak

6.3.5 Heat Power Required

The use of high temperature production (above T_{HWH}) capacity varies in the four scenarios in accordance with the dependance on HT Supply flow to maintain the LTD supply temperature. It is also the case capacity on a cold winter night is more valuable than capacity on a summer day when the merit order is dominated by waste heat recovery and there is a surfeit of heat production capacity. To address the difficulty in comparing the relative values of heat production capacity throughout the year a new metric was developed: residual capacity use, expressed in %-hours. It is calculated according to the equation below:

$$RCU = \frac{P_{LTD-HTS}}{P_{Network\ max} - P_{Network\ current}} \tag{13}$$

Where $P_{LTD-HTS}$ is the new high temperature heat demanded by the LTD after heat recovery and $P_{Network\ max}$ and $P_{Network\ Current}$ are the peak capacity and current production rate of heat in the existing high temperature network.

It can be seen that if the demand for HT supply flow required the last available unit of capacity for a single hour the residual capacity use for that hour would be 100%h. Similarly, if the LTD required an additional unit of heat capacity for an hour when there were 1000 units available, the residual capacity use would be 0.1%h for that hour.

In Figure 65, the residual capacity use is summed for all hours of the year for each supply scenario. Utilising the HTR flow in S1 decreases the use of HT supply capacity by 13%, introducing a mid-temperature waste heat stream in S2 decreases it by 62%, and in S3 designating the HP as the primary heat supply technology removes the dependance on HT Supply.

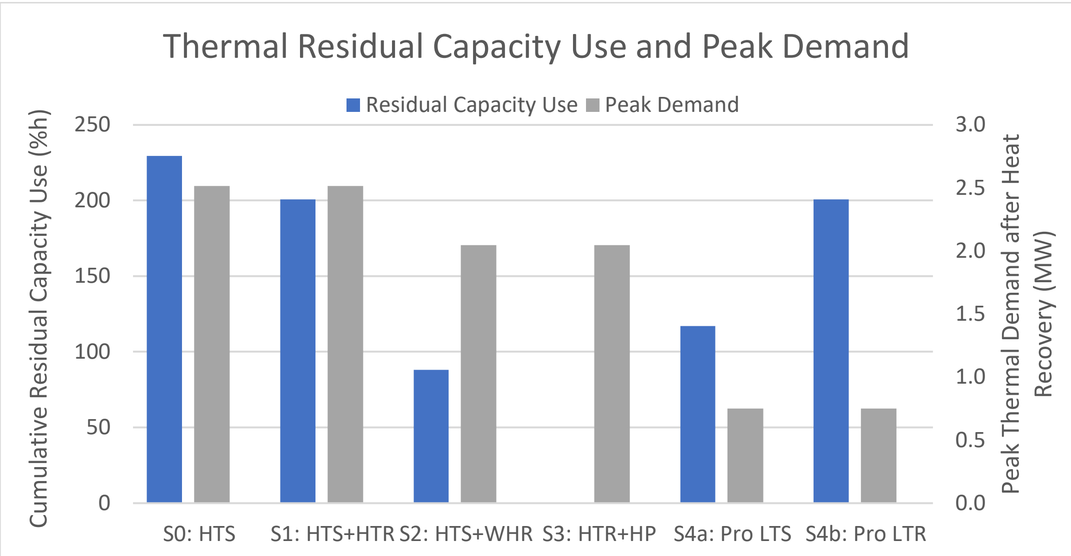

Figure 65: Thermal Residual Capacity Utilisation and Peak Demand after heat recovery of S0-S4

The annual net new high temperature heat requirements after heat recover, seen in Figure 66, follow a similar trajectory to the residual capacity use above.

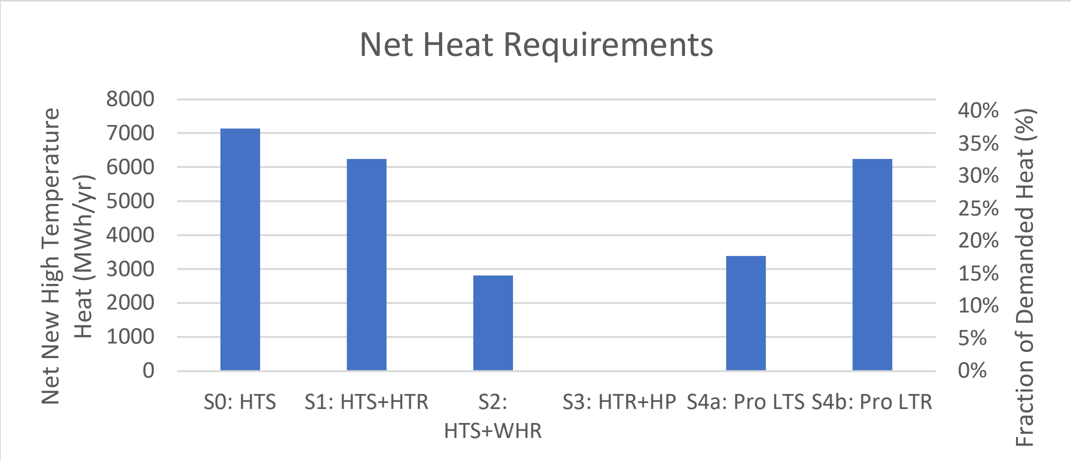

Figure 66: Net new high temperature heat requirements after heat recovery

The use of the 3rd Pipe reduces net heat requirements after heat recovery by 7 MWh/yr in the high temperature supply S0 and 5 MWh/yr in the low temperature supply S1, S2 , and S3. This amounts to a negligible (<0.05%) fraction of heat supply.

6.3.6 Network Heat Losses

The supply line produces the large majority of losses from the distribution network in the LTN, 81-82% in the HT supply scenario S0 and 76-79% in the LT supply scenarios. In LT supply scenarios total network heat losses are reduced by 10% (S3b) to 17% (S4a), almost entirely from reductions in the supply line losses.

The addition of a 3rd Pipe has two effects on network losses. First, the heat loss from the return line is reduced by 9% in HT scenarios and 8% in LT scenarios due to the lower return line temperature. Second, losses from the 3rd Pipe appear and more than make up for the reduction in losses from the return line[25]. The total network losses in 3rd Pipe systems thereby increases by 3% in LT supply scenarios and 2% in the HT supply scenario.

[25] Some of this could be avoided by right-sizing the 3rd Pipe. It is recalled from Section 243.4.2: Dimensioning the Network that the 3rd Pipe was implemented with the same diameter pipes as the return network. Even so, the losses here would represent a “worse case” scenario with an oversized 3rd Pipe.

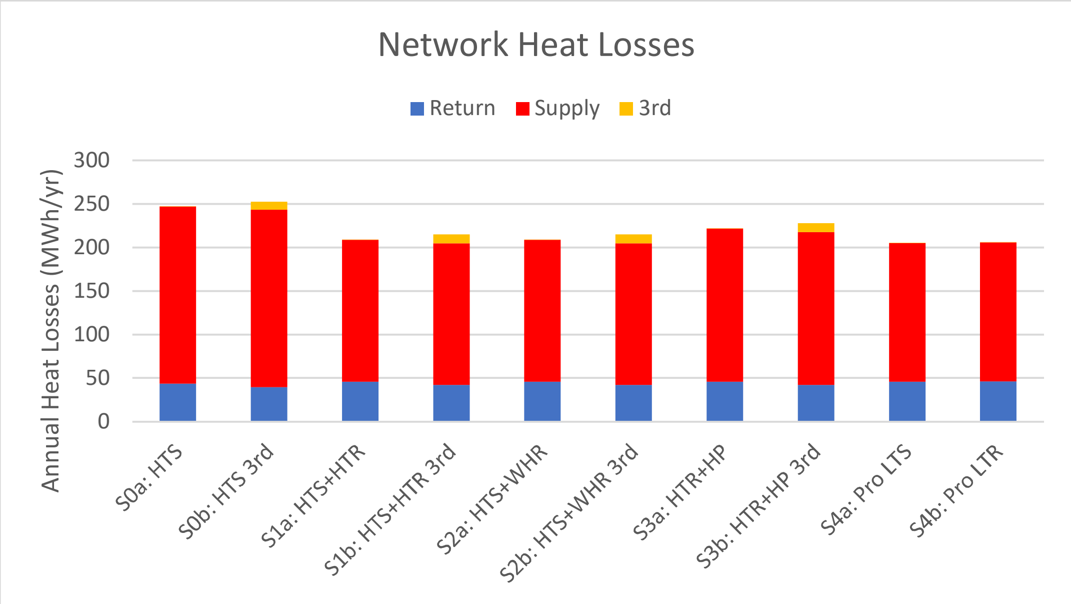

Figure 67: Network Temperature Losses for all scenarios

Given that heat losses amount for 8-15% of production in Swedish district heating networks it seems likely that the 1.1%-1.3% assessed by this model is a significant underestimation of the heat losses in the proposed network, even accounting for the reduced losses due to lower temperature supply and return lines. This is likely due to an underestimation of the coefficient of heat transfer for the network pipes, which serves as an input into the PandaPipes model. Nonetheless, the relative relationships between the scenarios appear to be reasonable.

7 Sensitivities

7.1 Network Temperature Control

To investigate how recirculation flow in the network would impact the supply temperature requirements the maximum temperature rise of the LTD supply temperature above the nominal 65°C level is changed from 5°C to 2°C for the S1b: Utilising HT Return with a 3rd Pipe. This change increases the amount of recirculation flow in the substations to reduce network temperature loss when demand is low. As can be seen below Figure 68 this change only impacts hours when the outside temperature is above 10°C.

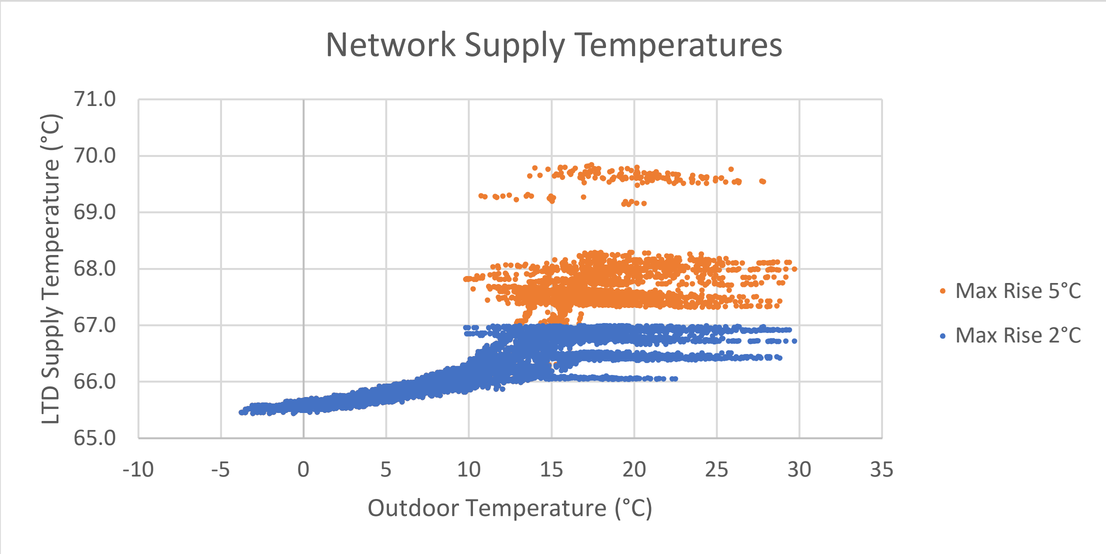

Figure 68: Change in Supply Temperatures with 5°C and 2°C Max Permitted Increase in T_{LTS}

The reduction of supply temperatures was achieved with a relatively small amount of recirculation flow, 1535m³ over the 2430 hours a substation bypass is operational. This amounts to 61 MWh of energy, or 0.3% of the annual district supply of 19,196 MWh. While there is a slight increase in heat losses from the 3rd Pipe, this is more than offset by a decrease in the supply line losses, as seen in Figure 69. Overall, there is a very slight decrease in network heat losses of -0.3%.

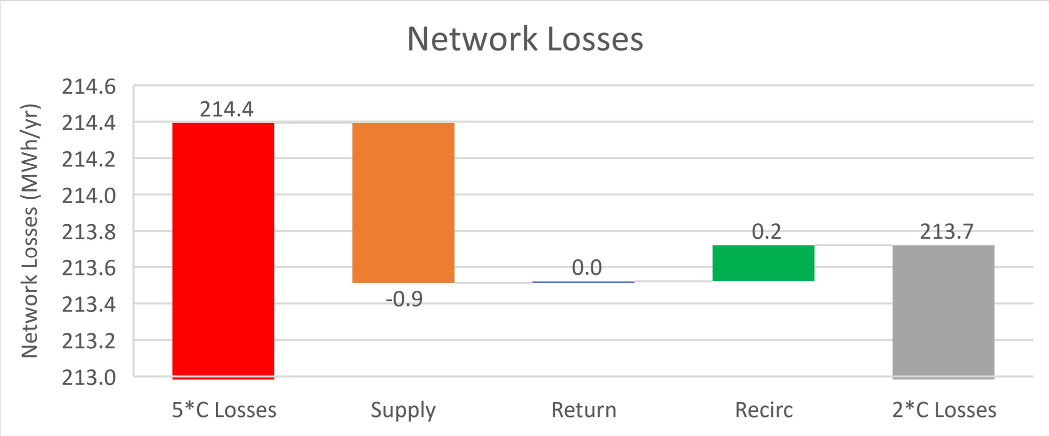

Figure 69: Change in Network Heat Losses between 5 and 2 Max Permitted Rise

7.2 3rd Pipe Diversion Temperature

Within the highly temperature efficient district, and utilising a diversion temperature of 40°C and a maximum supply temperature rise of 5°C, the 3rd pipe operates in a near binary state, as noted in Section 6.2.8: Effects of the 3rd Pipe. Seen in Figure 70 below, more than 90% of the return flow is diverted into the 3rd Pipe in 400 hours of the year, and into the return line for the remainder. If the objective of the 3rd pipe is to prevent mixing of high and low temperature return flows, having the vast majority of flow in either one pipe or the other is not effective.

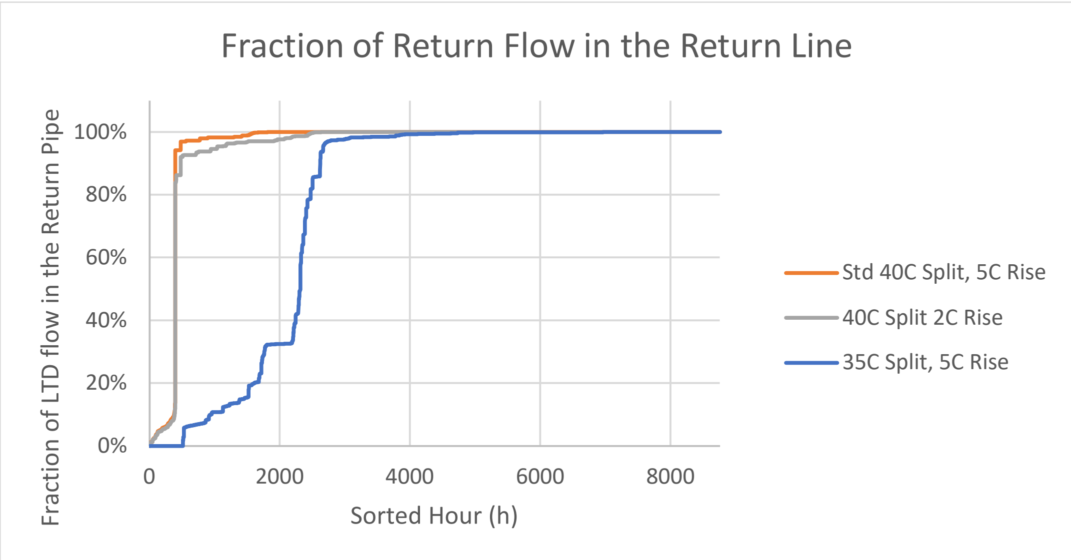

Figure 70: Fraction of Return Flow in the Return Line

It can also be seen in Figure 70 that decreasing the maximum supply temperature from 5°C to 2°C as discussed in above in Section 7.1: Network

Temperature Control has a relatively small increase on the amount of 3rd pipe diversion relative to lowering the diversion temperature.

Reducing the diversion temperature to 35°C increased the flow diversion, seen in Figure 70 (allowing for effective temperature separation and heat recovery) and the 3rd Pipe's use at differing demand levels. However the benefits still fall mainly in periods of low demand and have a somewhat high degree of binary operation, seen below in Figure 71.

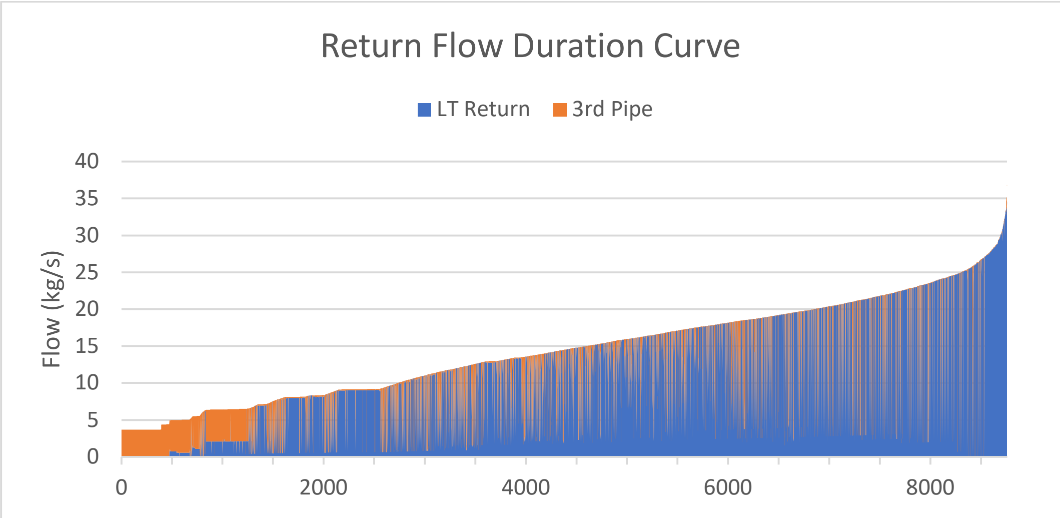

Figure 71: Return Flow Duration Curve with 35°C Diversion Temperature

8 Conclusion

This work analysed several methods of supplying district heat to a new low demand highly temperature efficient district in Stockholm utilising a low temperature network connected to an existing high temperature district heating network. The key focus areas were the possibilities for heat recovery created by this new district, the emissions produced by supplying it, and the utilisation and intensity of electricity in supplying the LTD. To accurately account for emissions in the case of a significantly decarbonised high temperature network, high resolution data from the emissions of grid electricity was incorporated in a method that has not been utilised in this application before. In addition, the net heat demand and heat recovery possibilities made possible by the new low temperature district were quantified and divided into temperature ranges in a novel approach. This approach extends the discussion of heat requirements of the new low temperature district beyond a net heat requirement and allows a DHN operator to place values representing their own complex operations on the quantified heat recovery possibilities.

It was found that in significantly decarbonised DHNs the drive to electrify heating can significantly increase the emissions of supplying a district, even with Swedish grid electricity, as among the scenarios analysed the sea-source heat pump produced the most emissions both when heat recovery possibilities were utilised and when they were not. The lowest emissions were produced when a waste heat source was utilised and delivered to the LTD by the existing network.

It was also found that both the scenarios utilising a mixture of temperature levels available within the existing DHN, such as HT supply, HT return, and a waste heat source, produced the highest utilisation of the connected electrical power capacity. Electrification of heating via the sea source heat pump produced the lowest utilisation, while prosumer scenarios with higher COPs performed slightly better. The utilisation of connected electrical capacity is already an issue in capacity constrained networks, such as Stockholm, and may become more so in the future as several services strive to electrify concurrently.

This work showed that utilising the existing DHN alongside new operating strategies and temperature efficient buildings offer the lowest emissions in a significantly decarbonised heating network.

9 Future Work

This work could be extended in several directions gain more insight into the operational complexity of DHNs.

- The capital and operational costs of the scenarios proposed could be evaluated
- The heat supply operational strategy for the LTD could be reconfigured to minimise emissions using a marginal emissions signal for both network heat supply and electricity
- Further investigation of when and how the 3rd pipe would be cost effective
- Building connection requirements could be developed to ensure high performance of the LTDH system
- Include the analysis of a DCN alongside the LTN as a means of reducing district electrical load through higher chiller efficiency and improving heat recovery throughout the year
- The residual capacity use of district's electrical network could be evaluated under these scenarios, and effects that installing a DCN would have on this

10 Bibliography

[1] Stockholms Stad, ‘Bostäder, förskolor och handel i Kolkajen’, *Stockholm växer*, May 2021. https://vaxer.stockholm/projekt/kolkajen/ (accessed Jun. 08, 2021).

[2] M. Fischetti, ‘We Are Living in a Climate Emergency, and We’re Going to Say So’, *Scientific American*, Apr. 2021. http://www.scientificamerican.com/article/we-are-living-in-a-climate-emergency-and-were-going-to-say-so/ (accessed Apr. 13, 2021).

[3] I. Tiseo and Statistica, ‘Annual CO2 emissions worldwide 2019’, *Energy & Environment - Emissions*. https://www.statista.com/statistics/276629/global-co2-emissions/ (accessed Mar. 15, 2021).

[4] IEA, ‘After steep drop in early 2020, global carbon dioxide emissions have rebounded strongly’, *News*. https://www.iea.org/news/after-steep-drop-in-early-2020-global-carbon-dioxide-emissions-have-rebounded-strongly (accessed Mar. 15, 2021).

[5] ‘Net Zero by 2050 - A Roadmap for the Global Energy Sector’, IEA, 2021.

[6] L. La Fleur, *Energy renovation of multi-family buildings in Sweden : An evaluation of life cycle costs, indoor environment and primary energy use, and a comparison with constructing a new building*, vol. 2008. Linköping: Linköping University Electronic Press, 2019. doi: 10.3384/diss.diva-160305.

[7] J. Niskanen, ‘Mainstreaming Passive Houses: A study of energy efficient residential buildings in Sweden’, Linköping University, Linköping, 2018. Accessed: May 16, 2021. [Online]. Available: https://liu.diva-portal.org/smash/get/diva2:1264439/FULLTEXT01.pdf

[8] N. Bertelsen and B. Vad Mathiesen, ‘EU-28 Residential Heat Supply and Consumption: Historical Development and Status’, *Energies*, vol. 13, no. 8, p. 1894, Apr. 2020, doi: 10.3390/en13081894.

[9] ‘Stockholm Innovates District Heating with New Solutions and Renewable Sources | Best practice’, *Smart City Sweden*. https://smartcitysweden.com/best-practice/401/stockholm-innovates-district-heating-with-new-solutions-and-renewable-sources/ (accessed Mar. 16, 2021).

[10] P.-O. Johansson, P. Lauenburg, and J. Wollerstrand, ‘Improved Cooling of District Heating Water in Substations by Using Alternative Connection Schemes’, presented at the 22nd International Conference on

Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Foz do Igarcu, Brazil, 2009.

[11] S. Werner, ‘District heating and cooling in Sweden’, *Energy*, vol. 126, pp. 419–429, May 2017, doi: 10.1016/j.energy.2017.03.052.

[12] H. Lund *et al.*, ‘4th Generation District Heating (4GDH)’, *Energy*, vol. 68, pp. 1–11, Apr. 2014, doi: 10.1016/j.energy.2014.02.089.

[13] M. Arnaudo, M. Topel, and B. Laumert, ‘Techno-economic analysis of demand side flexibility to enable the integration of distributed heat pumps within a Swedish neighborhood’, *Energy*, vol. 195, p. 117012, Mar. 2020, doi: 10.1016/j.energy.2020.117012.

[14] ‘Kapacitetsutmaningen i elnäten’, Energimarknadsinespektionen, EiR2020:06, Sep. 2020.

[15] European Environment Agency, ‘Greenhouse gas emission intensity of electricity generation in Europe’, May 2021. https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-3/assessment (accessed May 26, 2021).

[16] Tomorrow and O. Corradi, ‘Estimating the marginal carbon intensity of electricity with machine learning’, Jul. 2018. https://www.tmrow.com/blog/marginal-carbon-intensity-of-electricity-with-machine-learning/ (accessed Mar. 09, 2021).

[17] A. Volkova, I. Krupenski, H. Pieper, A. Ledvanov, E. Latõšov, and A. Siirde, ‘Small low-temperature district heating network development prospects’, *Energy*, vol. 178, pp. 714–722, Jul. 2019, doi: 10.1016/j.energy.2019.04.083.

[18] L. Brange, J. Englund, and P. Lauenburg, ‘Prosumers in district heating networks – A Swedish case study’, *Appl. Energy*, vol. 164, pp. 492–500, Feb. 2016, doi: 10.1016/j.apenergy.2015.12.020.

[19] Energimyndigheten och SCB, ‘El-, gas- och fjärrvärmeförsjningen 2019’, EN 11 SM 2001, Nov. 2020.

[20] PlanHeat, ‘Project Brief’, *PlanHeat*. http://planheat.eu/project-brief (accessed May 25, 2021).

[21] Fraunhofer Institute for Energy Economics and Energy System Technology and University of Kassel, ‘About pandapipes’, 2021. https://pandapipes.readthedocs.io/en/latest/ (accessed Apr. 13, 2021).

[22] Fraunhofer IEE and University of Kassel, ‘About pandapower’, 2021. https://pandapower.readthedocs.io/en/latest/about.html (accessed May 25, 2021).

[23] ‘Optimization with PuLP — PuLP 2.4 documentation’. https://coin-or.github.io/pulp/ (accessed Apr. 13, 2021).

[24] H. Averfalk and S. Werner, ‘Essential improvements in future district heating systems’, *Energy Procedia*, vol. 116, pp. 217–225, Jun. 2017, doi: 10.1016/j.egypro.2017.05.069.

[25] M. Ranta-Korpi, ‘Aurinko- ja ilmalämmön hyödyntäminen maalämpöjärjestel- män energiatehokkuuden parantamisessa’, Aalto-yliopisto, Espoo, 2018.

[26] H.-O. K. Hjorth, R. Antonsson, T. L. Söderberg, S. Wellander, E. Olsson, and K. Fant, ‘Implementation of the EPBD in Sweden’, Boverket and Swedish Energy Agency, 2016. Accessed: Jun. 07, 2021. [Online]. Available: https://epbd-ca.eu/outcomes/2015-2018/book2018/countries/sweden/

[27] E. Jalilzadehazhari, G. Pardalis, and A. Vadiee, ‘Profitability of Various Energy Supply Systems in Light of Their Different Energy Prices and Climate Conditions’, *Buildings*, vol. 10, no. 6, p. 100, May 2020, doi: 10.3390/buildings10060100.

[28] ‘F:101 District Heating Substations: Design and Installation Technical Regulations’. Energi Företagen, Feb. 2016.

[29] ‘2005 ASHREA Handbook - Fundamentals (SI): Design Conditions for STOCKHOLM/ARLANDA, Sweden’. ASHREA, 2005.

[30] R. Lahdelma, ‘DH and DC Demand’. Aalto-yliopisto, Jan. 2020.

[31] Fortum Värme, ‘Installationsanvisningen Fjärrvärmecentral 2017’. Fortum Värme, 2017.

[32] Folkhälsomyndigheten, ‘Legionella’, *Object Borne Infection*, 2020. http://www.folkhalsomyndigheten.se/livsvillkor-levnadsvanor/miljohalsa-och-halsoskydd/tillsynsvagledning-halsoskydd/smitta-kopplad-till-objekt/legionella/ (accessed Apr. 18, 2021).

[33] Folkhälsomyndigheten, ‘Skötsel av vattensystem’, *Legionella*, 2020. http://www.folkhalsomyndigheten.se/livsvillkor-levnadsvanor/miljohalsa-och-halsoskydd/tillsynsvagledning-halsoskydd/smitta-kopplad-till-objekt/legionella/skotsel-av-vattensystem/ (accessed Apr. 18, 2021).

[34] ‘Guidelines for District Heating Substations’, Euroheat and Power, Oct. 2008.

[35] T. Lidberg, T. Olofsson, and L. Ödlund, ‘Impact of Domestic Hot Water Systems on District Heating Temperatures’, *Energies*, vol. 12, no. 24, p. 4694, Dec. 2019, doi: 10.3390/en12244694.

[36] S. Burke, J. von Seth, T. Ekström, C. Maljanovski, and M. Wiktorsson, ‘Mapping of Domestic Hot Water Circulation Losses in Buildings – Preliminary Results from 134 Measurements’, *E3S Web Conf.*, vol. 172, p. 12009, 2020, doi: 10.1051/e3sconf/202017212009.

[37] P. Salazar Navalon, ‘Evaluation of Heat Losses from a Domestic Hot Water Circulation System’, University of Gävle, Gävle, 2015. Accessed: May 21, 2021. [Online]. Available: http://www.diva-portal.org/smash/get/diva2:842736/FULLTEXT01.pdf

[38] P.-O. Johansson, ‘Buildings and district heating: contributions to development and assessments of efficient technology’, Lund University, Lund, 2011.

[39] Svensk Fjärrvärme, ‘Fjärrvärmecentralen Kopplingsprinciper Rapport 2009:3’. Svensk Fjärrvärme, 2009.

[40] M. Köfinger, D. Basciotti, and R.-R. Schmidt, ‘Reduction of return temperatures in urban district heating systems by the implementation of energy-cascades’, *Energy Procedia*, vol. 116, pp. 438–451, Jun. 2017, doi: 10.1016/j.egypro.2017.05.091.

[41] A. Volkova *et al.*, ‘Energy cascade connection of a low-temperature district heating network to the return line of a high-temperature district heating network’, *Energy*, vol. 198, p. 117304, May 2020, doi: 10.1016/j.energy.2020.117304.

[42] P. Leoni, R. Geyer, and R.-R. Schmidt, ‘Developing innovative business models for reducing return temperatures in district heating systems: Approach and first results’, *Energy*, vol. 195, p. 116963, Mar. 2020, doi: 10.1016/j.energy.2020.116963.

[43] J. Song, F. Wallin, H. Li, and B. Karlsson, ‘Price Models of District Heating in Sweden’, *Energy Procedia*, vol. 88, pp. 100–105, Jun. 2016, doi: 10.1016/j.egypro.2016.06.031.

[44] T. Rosén and L. Ödlund, ‘Active Management of Heat Customers Towards Lower District Heating Return Water Temperature’, *Energies*, vol. 12, no. 10, p. 1863, May 2019, doi: 10.3390/en12101863.

[45] M. Rämä and K. Sipilä, ‘Transition to low temperature distribution in existing systems’, *Energy Procedia*, vol. 116, pp. 58–68, Jun. 2017, doi: 10.1016/j.egypro.2017.05.055.

[46] D. Schmidt *et al.*, ‘Low Temperature District Heating for Future Energy Systems’, *Energy Procedia*, vol. 116, pp. 26–38, Jun. 2017, doi: 10.1016/j.egypro.2017.05.052.

[47] M. Arnaudo, J. Dalgren, M. Topel, and B. Laumert, ‘Waste heat recovery in low temperature networks versus domestic heat pumps - A techno-economic and environmental analysis’. ND.

[48] R. Lund, D. S. Østergaard, X. Yang, and B. V. Mathiesen, ‘Comparison of Low-temperature District Heating Concepts in a Long-Term

Energy System Perspective', *Int. J. Sustain. Energy Plan. Manag.*, pp. 5-18 Pages, Mar. 2017, doi: 10.5278/IJSEPM.2017.12.2.

[49] L. R. Adrianto, P.-A. Grandjean, and S. Sawalha, 'Heat recovery from CO2 refrigeration system in supermarkets to district heating network', Valencia, 2018, p. 9.

[50] Stockholm Exergi, 'Open District Heating', *Öppen Fjärrvärme*. https://www.opendistrictheating.com/ (accessed Dec. 28, 2020).

[51] Fortum, 'Öppen Fjärrvärme Koncepthandbok'. Fortum, 2015.

[52] S. Sawalha, 'Investigation of heat recovery in CO2 trans-critical solution for supermarket refrigeration', *Int. J. Refrig.*, vol. 36, no. 1, pp. 145–156, Jan. 2013, doi: 10.1016/j.ijrefrig.2012.10.020.

[53] Stockholm Exergi, 'Så funkar fjärrkyla'. https://www.stockholmexergi.se/sa-funkar-det-med-fjarrvarmen/sa-funkar-fjarrkyla/ (accessed Mar. 16, 2021).

[54] Tomorrow, 'Live CO_2 emissions of electricity consumption', *Electricity Map*. http://electricitymap.tmrow.co (accessed Mar. 09, 2021).

[55] M. Killendahl, 'Marginal Generation Mix SE'. Tomorrow, Aug. 25, 2020.

[56] Tomorrow, 'Live CO_2 emissions of electricity consumption - Sweden', *Electricity Map*. https://www.electricitymap.org/zone/SE (accessed Mar. 09, 2021).

[57] M. Killendahl, 'Marginal Emissions SE'. Tomorrow, Aug. 25, 2020.

[58] M. Killendahl, 'Electricity Flows and Emissions Sweden'. Tomorrow, Aug. 25, 2020.

[59] Stockholms Stad, 'Program för hållbar stadsutveckling - Norra Djurgårdsstanden visar vägen mot en hållbar framtid'. Stockholms Stad, 2017.

[60] S. Klugman and R.-M. Ågren, 'Louddens energisystem: Bedömning av genomförbarhet och samhällsekonomisk nytta för tre energialternativ'. Sweco, 2017.

[61] Utopia, 'Sveriges högsta byggnad i en helt ny stadsdel', *Project*, 2017. http://www.utopia.se/se/projekt/loudden (accessed Apr. 30, 2021).

[62] K. Thullner, 'Low-energy buildings in Europe - Standards, criteria and consequences', p. 165.

[63] K. E. Thomsen *et al.*, 'EPBD Implementation in Denmark - Status in December 2016', Danish Energy Agency, 2018. Accessed: Jun. 07, 2021. [Online]. Available: http://epbd-ca.eu/wp-content/uploads/2018/08/CA-EPBD-IV-Denmark-2018.pdf

[64] R. Lahdelma, ‘DHC: Distribution’. Aalto-yliopisto, 2020.

[65] O. Eriksson and G. Finnveden, ‘Energy Recovery from Waste Incineration—The Importance of Technology Data and System Boundaries on CO2 Emissions’, *Energies*, vol. 10, no. 4, p. 539, Apr. 2017, doi: 10.3390/en10040539.

[66] N. Becker, L. Björnsson, and P. Börjesson, ‘Greenhouse gas savings for Swedish emerging lignocellulose-based biofuels - using the EU renewable energy directive calculation methodology’, Lunds Universitet, Lund, 104, 2017.

[67] I. Mawdsley, T. Wisell, H. Stripple, and C. Ortiz, ‘Revision of emission factors for electricity generation and district heating (CRF/NFR 1A1a)’, Swedish Meteorological and Hydrological Institute, Norrköping, Svenska Miljö Emissions Data No 194 2016, 2016.

[68] Knoema, ‘Cooling and heating degree days by NUTS 2 regions - Annual data - Stockholm’, *Knoema*, 2021. https://knoema.com//nrg_chddr2_a/cooling-and-heating-degree-days-by-nuts-2-regions-annual-data?geo=1025530-stockholm (accessed May 11, 2021).

[69] Stockholm Exergi, ‘Returntemperature Gärdet 2020’. Stockholm Exergi, Mar. 2021.

[70] G. Persson, G. Strandberg, L. Bärring, and E. Kjellström, ‘Beräknade temperaturförhållanden för tre platser i Sverige –perioderna 1961-1990 och 2011-2040’, SMHI, Nr 124, 2007.

[71] Stockholm Exergi, ‘Värtaverket: Stockholm Exergi, miljörapport 2018’, Stockholm Exergi, Stockholm, 2019.

[72] QGIS, ‘QGIS - The Leading Open Source Desktop GIS’, *Discover QGIS*. https://www.qgis.org/en/site/about/index.html (accessed Jun. 23, 2021).

[73] RINA-C, ‘PLANHEAT Tool Manual’. PlanHeat, 2019.

[74] L. REINHOLDT, J. KRISTOFERSSON, B. ZÜHLSDORF, and Et Al., ‘Heat pump COP, part 1: generalized method for screening of system integration potentials.’ International Institute of Refrigeration (IIR), 2018. doi: 10.18462/IIR.GL.2018.1380.

[75] S. Werner, ‘District Heating and Cooling’, in *Reference Module in Earth Systems and Environmental Sciences*, Elsevier, 2013, p. B9780124095489012000. doi: 10.1016/B978-0-12-409548-9.01094-0.

Appendix A: Heat Band Allocation Diagrams

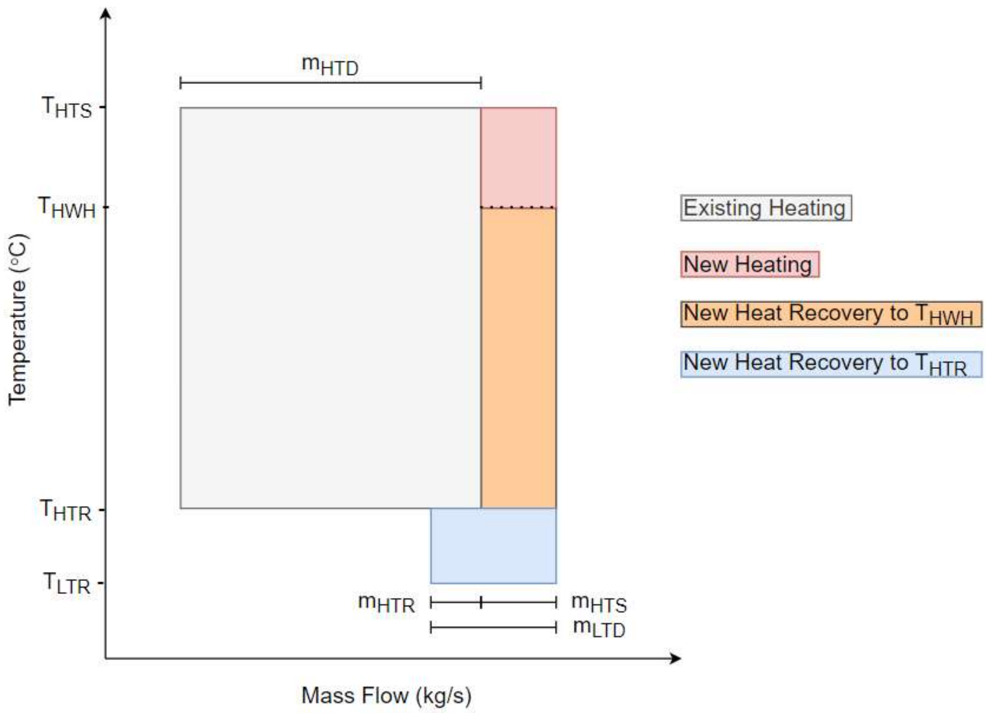

Figure 72: Heat Band Allocation Diagram for S1a: Utilising HT return flow

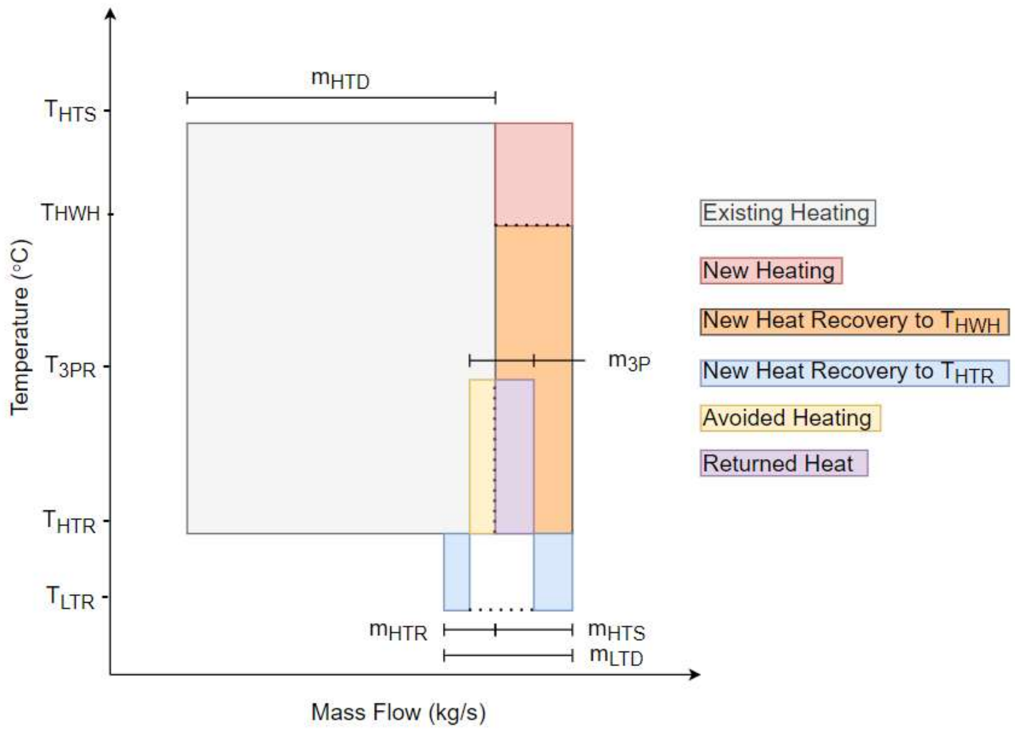

Figure 73: Heat Band Allocation Diagram for S1b: Utilising HT return flow with a 3rd Pipe

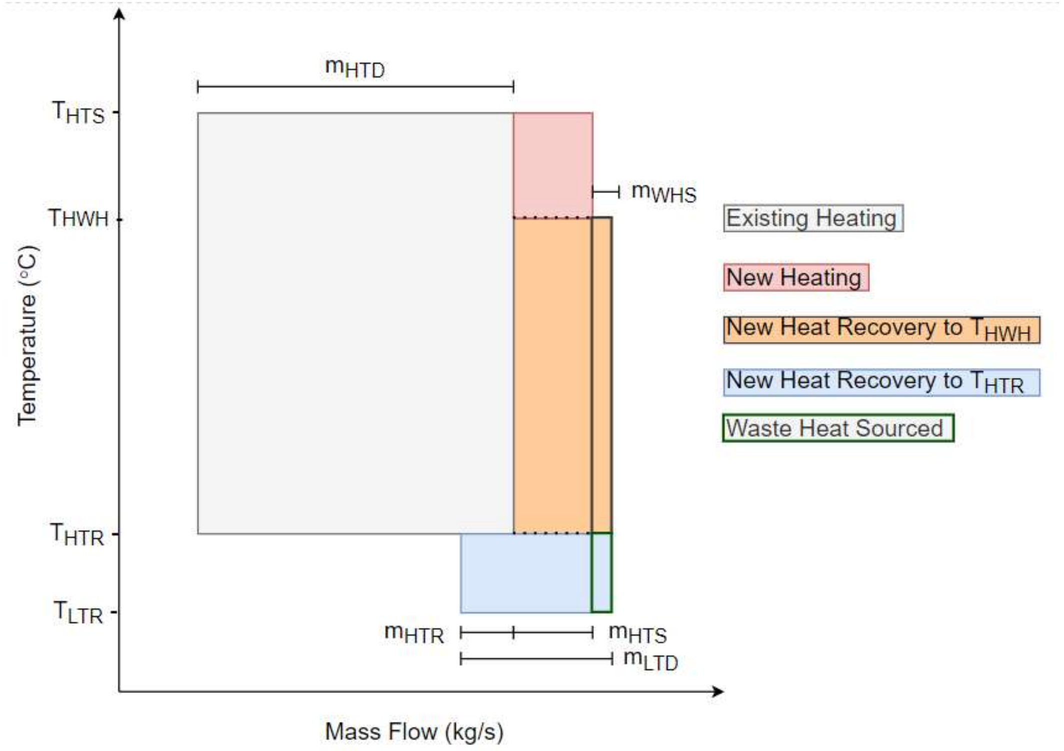

Figure 74: Heat Band Allocation Diagram for S2a: Utilising a Waste Heat Source

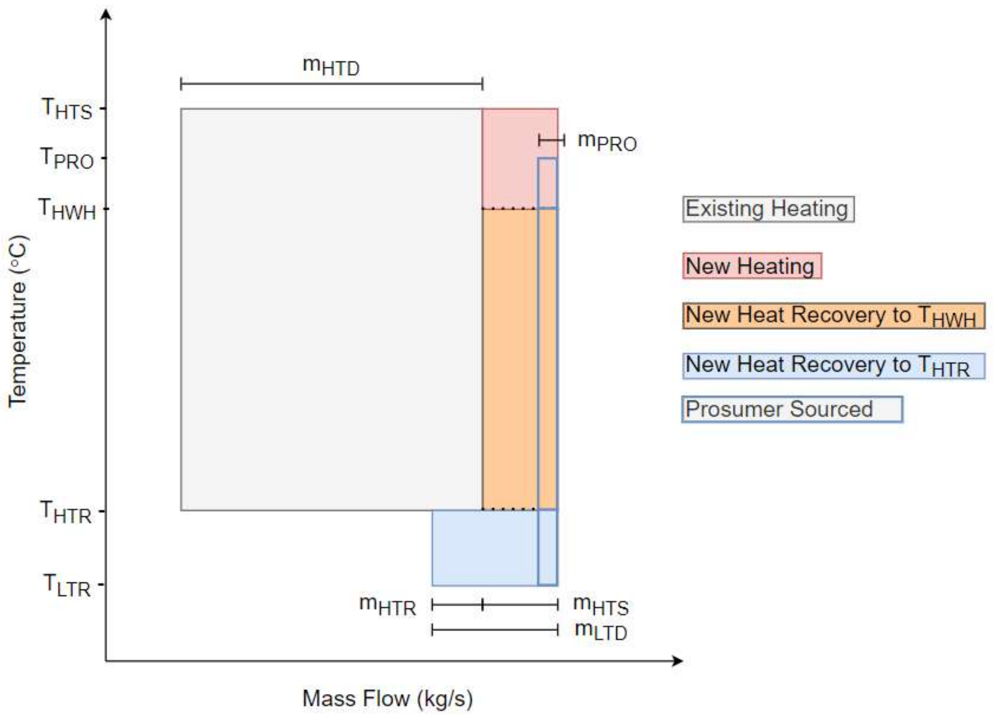

Figure 75: Heat Band Allocation Diagram for S4a: Prosumers to the LT supply

Figure 76: Heat Band Allocation Diagram for S4b: Prosumers to the LT return